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Contents of Volume XXVIII

NUMBER I

NUMBER II

NUMBER III

NUMBER IV

NUMBER V

NUMBER VI

NUMBER VII

NUMBER VIII

VOLUME XXVIII W. D. Walcott Jr

NUMBER 1

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EDITED BY

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ROLLIN T. CHAMBERLIN, Dynamic Geology

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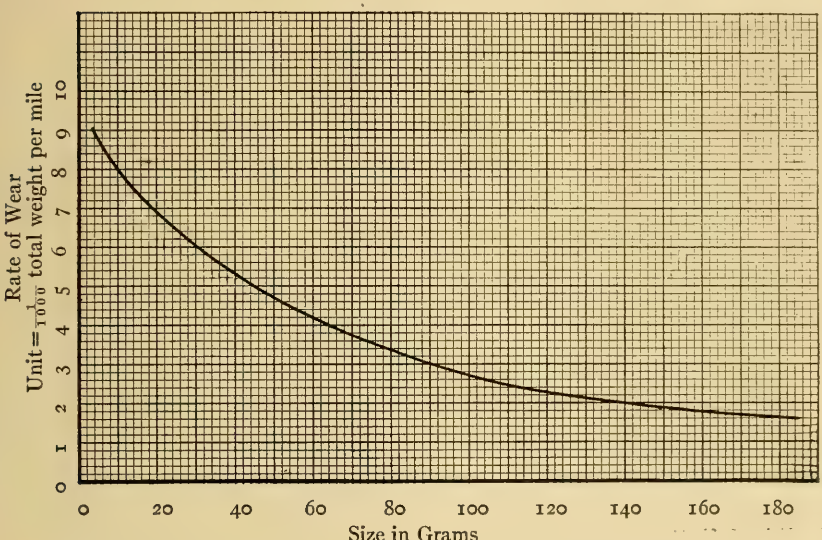
ERRATA

In Mr. Wentworth's article in the *Journal of Geology*, Volume XXVII, pages 507–21, a number of figures were incomplete and others not properly arranged. For the corresponding figures please substitute the following:



This curve is under the following conditions:

Rock—Niagara limestone
Barrel Vel.—27 R.P.M.
Barrel Diam.—24 inches
Flushed with water
Mixture—3,000 grams in 6½-inch compartment

FIG. 2.—Relation of rate of wear to size of cobble

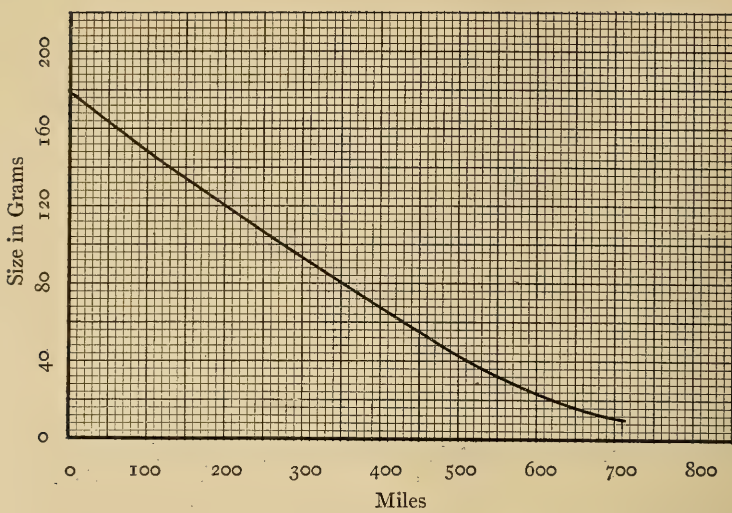


FIG. 3.—Relation of size to distance traveled. Ideal history of cobble starting at 178 grams' weight.

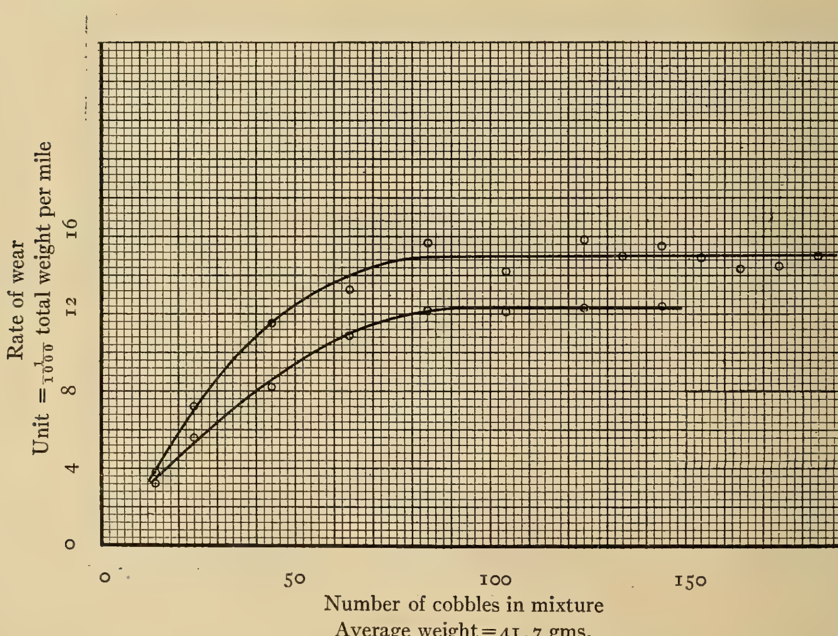
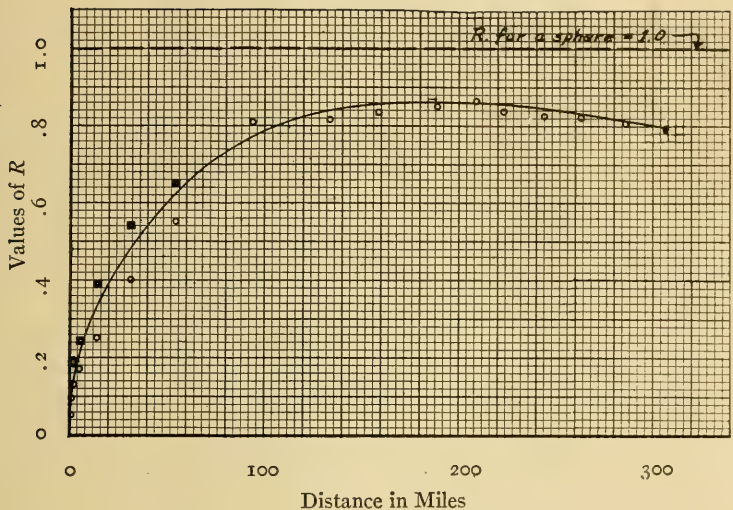


FIG. 5.—Effect of amount of mixture in compartment of drum



ROUNDING OF CUBES

FIG. 26.—Graph of values of R plotted against distance for the series illustrated in Figures 8 to 25.

r = radius of curvature of most convex point
d = diameter through same point

$$R = \frac{2r}{d}$$

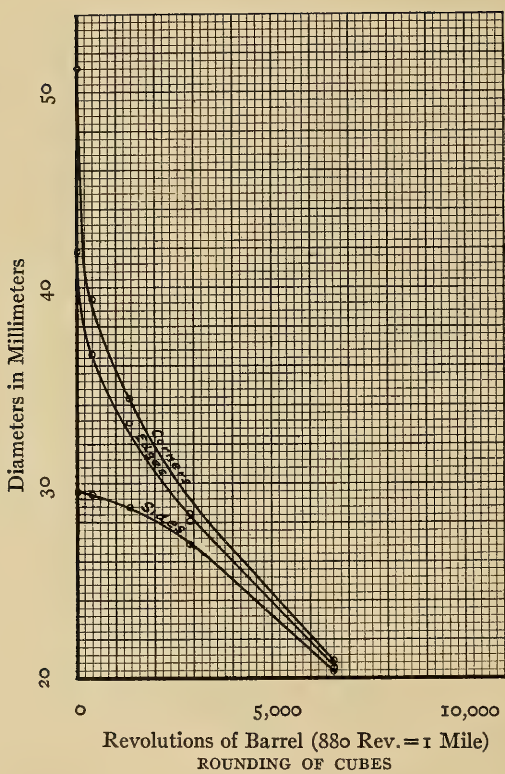
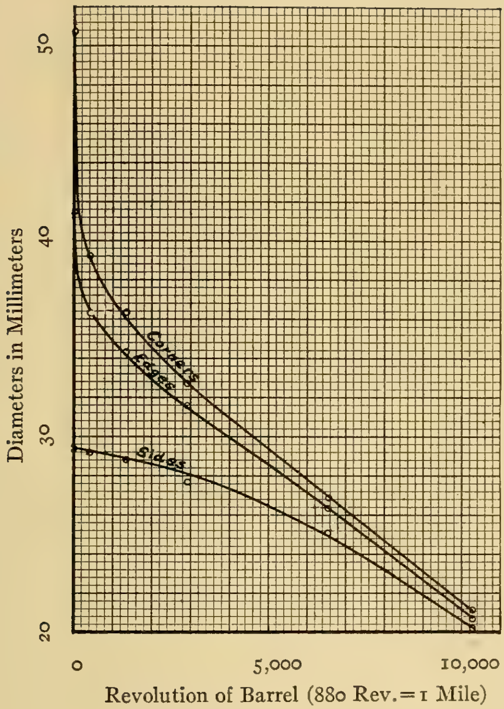


FIG. 27.—Showing convergence of diameters of cubes rounded by cobbles averaging 70 grams each.



ROUNDING OF CUBES

FIG. 28.—Showing convergence of diameters of cubes rounded by cobbles averaging 20 grams each.

VOLUME XXVIII NUMBER 1

THE
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JANUARY-FEBRUARY 1920

DIASTROPHISM AND THE FORMATIVE PROCESSES

X. THE ORDER OF MAGNITUDE OF THE SHRINKAGE OF THE EARTH DEDUCED FROM MARS, VENUS, AND THE MOON

T. C. CHAMBERLIN
The University of Chicago

PRELIMINARY CONSIDERATIONS

During the last century it was the prevalent view that the earth was once a white-hot liquid globe. It was a logical inference from this view that the subsequent shrinkage of the earth arose chiefly from a loss of heat and from effects incidental thereto. On critical inquiry, however, it was found that the contraction assignable to lowering of temperature was disappointingly small. On the other hand, it was found as field inquiry was extended that the sum total of surface shortening implied by foldings, crumplings, overthrusts, and similar evidence was distinctly large. As a result of these divergent disclosures, students of diastrophism came to feel not a little hesitation in following out fully and freely to their logical limits the trend of interpretations suggested by field evidence whenever very great shrinkage was foreshadowed. The restraint thus felt was much like that suffered during the same period from supposed limitation of geologic time, a restraint now happily removed.

A radically new aspect, however, was given to the whole problem of earth shrinkage when, near the opening of this century, it was

discovered that certain of the heaviest known atoms were spontaneously giving out heat as an incident of their own disintegration. It was found that if radioactive substances pervade the whole body of the earth as richly as they do the accessible portions, the heat generated by them would be much greater than the amount the earth is now discharging at its surface. The certainty that the earth had been cooling at once disappeared; it seemed quite as likely that the temperature of the earth was rising as falling and, so far as heat is concerned, the volume of earth quite as likely swelling as shrinking. This cut at the very roots of the former tenet that shrinkage was chiefly due to the lowering of the temperature. The possible potentialities of the new source of heat were not only embarrassing in themselves, but they made the great heat hypothetically inherited from the white-hot earth a superadded burden of embarrassment instead of the facile explanation of shrinkage and deformation it had once been supposed to be.

Nor was this all: It was obviously necessary to devise some special hypothesis to obviate the surplus of heat the radioactive substances would give if they had a uniform distribution throughout the interior of the earth. Since no pressure or other physical condition is known to reduce appreciably the thermal output of radioactivity, a restriction of the radioactive substances themselves to a shallow surface shell seemed the only hypothesis available. But here the tenet of a molten globe arose as a new form of embarrassment. The radioactive substances are exceptionally heavy, and in a liquid mass they should naturally concentrate toward the center, not toward the surface. Convection, of course, if it were sufficiently active, might be supposed to prevent much concentration toward the center, but convection carries down as well as up and tends to give a more or less uniform distribution—just the distribution the hypothesis is seeking to avoid.

Nor is this the limit of the embarrassments attending the old view. A molten state implies that the larger part of the potential resources of shrinkage were exhausted before the formation of a crust made a record of shrinkage possible, at least so far as shrinkage depends on arrangements and combinations of material. A molten state offers nearly ideal conditions for the physical adjustment of

all constituent elements and for such chemical combinations as are possible, except in so far as the heat itself stands in the way. With such extraordinary facilities for selective adaptation as were hypothetically offered by the passage of the earth substance from the assigned gaseous to the liquid state and thence at length on to the solidifying state, a large part of all possible adaptation to the demands of pressure—save those restrained by heat—should have taken place before the record of diastrophism began. About all shrinkage left to be registered would be the meager amount that might spring from cooling.

Thus in several vital ways the inherited theory of a molten earth came to be a source of embarrassment to investigators who were struggling with the specific demands made by the field evidences of actual diastrophism.

THE WORKING FITNESS OF THE ALTERNATIVE VIEW

However, the case was desperate only from the traditional point of view. These embarrassments may be avoided if the gaseo-molten hypothesis is replaced by some form of the view that the earth was built up by the accession of solid particles brought to the earth in succession at intervals. In an earth so built the aggregate should have retained very nearly its maximum resources of combination, adjustment, and compression, while at the same time it was contributing only a small measure of heat to embarrass the threatened oversupply from radioactivity.

Furthermore, this view affords an easy and natural explanation of the concentration of radioactive substances at the surface. Under this view the radioactive particles came to the earth at random with the rest of its material. Their spontaneous heat was readily radiated away until they became buried to depths that prevented its ready escape. They then tended to become centers of local liquefaction. In so far as this was realized they became enveloped in their own mobile products and were thus carried by the extrusive agencies up to the cold zone or the surface. The liquid blebs thus generated, carrying their self-heaters with them, were well equipped for making exchanges with the eutectic substances encountered on their way out and for concentrating these

in the ascending thread of lava, leaving behind the less eutectic substances. They were thus well fitted to fulfil three functions: (1) to flux their way upward, (2) to separate the more fusible material from the less fusible, and (3) to carry the former out to the cold zone or the surface, taking along the chief source of heat and the heat already generated. By thus draining away selectively the more fusible elements in the mixed material and raising the mean resistance of the rest to fusion, they help to maintain the solidity of the main mass. It is obvious that adjacent threads of hot self-heating lava must render one another assistance in mutually uniting and massing their forces for fusing their way outward. After such tracts have been drained of their more fusible substances and the conduits closed, new paths in ground less depleted of its eutectic material would naturally be chosen and thus the selective work should at length cover the whole field and raise its mean fusion-point, while the self-heating radioactive particles were more completely removed.

At all stages of this selective process it is held that the differential stresses of the earth body lent effective aid in extruding the liquid matter. The great pervasive stresses of the earth, static and dynamic alike, are intensest in the deep interior and graduate outwardly. The differential components of these are well suited to squeeze toward the surface the liquefying portions of the interior matter about as fast as these accumulate in sufficient quantities to respond readily to such stresses, while the liquids themselves readily yield to the rise by reason of their heated state and the gases they gather to themselves. To this doubly facilitated extrusion of liquid matter carrying its special thermal source with it is assigned the function of clearing the depths of their original radioactive substances and of their heat products, with the incidental effect of perpetuating the solid state of the earth as a whole.

If the simile may be pardoned, the liquid threads may be likened to the sweat pores of an organic body, regulating its temperature by a natural perspiratory system. The pools of lava that at times accumulate at the surface function as the sweat drops of the earth body. They seem large, to be sure, in terms of ordinary

measure, but they are really quite minute when compared with the 260,000,000,000 cubic miles of the earth mass.

It will be noted that this view is a reversal of the old interpretation. Instead of being a residual effect of former excessive heat, extrusive igneous action is initiated automatically within the body and forms a regulative system through which the solidity of the globe is maintained. The extrusive action is at the same time merely a minor feature in a general genetic process that has conserved the potential resources of shrinkage and rendered them available at such successive stages in the history of the planet's evolution as developed the conditions necessary to call them into action.

But, notwithstanding the ampler possibilities of shrinkage which this newer view places at the command of students of diastrophism, the pall of restraint has not as yet been wholly lifted. Thus far there has been no well-grounded estimate of the total earth shrinkage that has actually taken place. Even a theoretical estimate of the shrinkage available for interpretative assignment is still lacking. Workers in this field are thus still more or less under the shadow of restraint. Research will certainly proceed with more equipoise if workers can feel wholly untrammeled by supposed limitations in following to their logical conclusions any leadings of evidence they may encounter, even though its demands may be greater than general considerations have thus far seemed to warrant.

THE SPECIFIC FIELDS THAT YIELD DIASTROPHIC EVIDENCE

A glance at the field evidences of diastrophism will further prepare the way for a study of the probabilities of the case. Diastrophism is displayed in three great fields. These are closely related, to be sure, but yet sufficiently different to require individual recognition.

I. The first embraces the deformations of the distinctly stratified terranes, chiefly those of the Paleozoic and later ages. These are relatively accessible, and the constituent formations usually so far retain their individuality as to be susceptible of being satisfactorily traced throughout the whole tract involved in the deformation under study.

II. The second embraces the complicated distortions and the metamorphosed phases of the Proterozoic and Archean complexes. Usually these are only partially accessible, and the profound changes they have undergone present formidable difficulties in addition.

III. The third includes the deeper and more massive deformations of the earth body. These can be regarded as accessible only in a logical sense by means of indirect evidences or remote intimations, or by a priori considerations.

I. In the more surficial of these three fields estimates of crustal shortening have been made from time to time in the past, but in the main these have been confined to linear shortening; they have not included the depths involved in the shortening. This is necessary for computing their total quantitative values. Nor has there usually been any determination of the under-configuration of the distorted masses. This carries a very important part of the specific significance which the diastrophism embodies. A notable beginning has been made in adding these two neglected factors and increasing at the same time the reliability of the estimate of the linear factor.[1] But the labor involved in these more adequate determinations is so large that much time must pass before a sufficient number of such determinations can be made available for a total estimate of the shrinkage involved in even the limited field to which the method is adapted.

II. In the Proterozoic-Archean field there is little ground to hope for any general application of these superior methods, partly because of the large measure of concealment of the terranes and partly because of the excessive intricacy of the structure and the frequent changes in petrologic nature which render sharp identifications of the borders of the several members of the terrane throughout the whole folded tract impracticable. The difficulties of this field are formidable in the extreme. No one, so far as I know, has thus far had the temerity to offer an estimate of the amount of shortening implied by the intricate crumpling of these

[1] Rollin T. Chamberlin, "The Appalachian Folds of Central Pennsylvania," *Jour. of Geol.*, XVIII (1910), pp. 228–51; "The Building of the Colorado Rockies," *ibid.*, XXVII (1919), pp. 145–64, 225–51.

old formations on any great circle of the earth. That it was large, however, goes without the saying.

But, taken at their best, the deformations in these two fields are merely surficial. Such foldings as are accessible are mere wrinklings of the skin of the earth body, mere lineaments of the face of the earth. They have about the same relation to the effective framework of the earth body as the shriveled integument of an old man has to the bony skeleton that chiefly gives form to his figure.

III. The deeper deformations of the earth have been little more than a field for the imagination thus far. And yet they have given rise to indirect and implied evidences. There are the protrusions of the continents, the sags of the sub-oceanic basins, and the general configurations of the globe. There are tidal, seismic, magnetic, and other dynamic lines of approach. Great light has been thrown on the problems of the interior by the brilliant determination of the value and nature of the body tide and the elastic rigidity of the earth by Michelson and Gale on the experimental side,[1] and Moulton on the mathematical side.[2] The seismic evidences gathered by many observers indicate that the elasticity of the earth increases downward faster than the density for at least a depth that involves much more than half the volume of the earth. These trenchant determinations bear vitally on the interpretation of the internal deformation of the earth.

The lines of approach now available for an interpretation of the master-features of the earth's surface promise at least some insight of value into the earth's fundamental diastrophism. I have ventured to interpret these master-features as simply the adult products of a segmentation that sprang from primitive shrinkage stimulated and shaped by oscillating rotation and tidal strains.[3] Under this view there are cogent reasons for assuming that the original segments were more or less unequal and asymmetric, and

[1] A. A. Michelson and H. G. Gale, "The Rigidity of the Earth," *Jour. of Geol.*, I (1919), pp. 585–601.

[2] F. R. Moulton, "Theory of Tides in Pipes on a Rigid Earth," *Astrophys. Jour.*, L (1919), pp. 346–55.

[3] *The Origin of the Earth* (1916), pp. 200–224.

that the large inequalities and asymmetries now observed are largely due to later shiftings, distortions, and outgrowths of the primitive elements. These then are the special subjects of study in the third field of diastrophism.

THE PARTICULAR OCCASION FOR THIS INQUIRY

Now in a recent study of what could plausibly be assigned to original irregularity in segmentation and what then remained to be assigned to subsequent movements and unequal growths, I was led to see, or to think I saw, evidence of a system of shiftings and of unequal growths which marshaled themselves in a singularly rational way as though they were due to systematic causes of a general nature. The particular adjustments appeared to be such as were directly implied by the configurations which the great features now bear. By reasoning back from the present configurations to the assigned primitive configurations, rather specific amounts of shiftings and deformations, abetted by unequal outgrowths, seemed to be indicated. The amounts of these shiftings were distinctly larger than the movements commonly assigned to diastrophisms in the surficial fields. Because of this largeness the question, How much shrinkage can reasonably be assigned the earth during its whole history? came up in a new and specific form, and with especial piquancy by reason of unexpectedly exacting demands.

COMPARISON BETWEEN THE EARTH AND ITS NEIGHBORS

In casting about for some independent means of estimating such reasonable possibilities or even probabilities of shrinkage as there might be under the later view of the constitution of the earth, a comparison of our planet with its near neighbors, the moon, Venus, and Mars, suggested itself, as also a comparison with an ideal earth built of material of the average meteoritic type.

The earth, Venus, Mars, and the moon form a little group of closely related bodies revolving in the inner part of the sphere of control of the sun under very similar dynamic conditions. We naturally think of them as widely deployed, but, taken all together, the little group spans less than 3 per cent of the radial reach of

the solar system and probably not more than a thousandth part of the radius of the sun's sphere of control. This last is the more significant standard, for the sun's sphere of control is the dynamic field within which the planets had their origin and have ever since had their being. It is therefore a reasonable inference that the members of the little group shared much the same evolutionary conditions, were formed in much the same way, and of much the same material. But even if there was some gradation in the nature of the material due to position in the system—which we will consider later—its effects are measurably equated in the comparisons, because Mars lies outside the earth and Venus inside, while the moon, as a member of the earth system, presumably partook of the common material from which both earth and moon were derived, though perhaps not in precisely the same way. At any rate, though some differences of original material must be presumed to have entered into the formation of these four bodies, such differences could scarcely have been at all radical. Besides, it will be seen later to be possible to deduce the more important differences which affected the selection of material in the formation of these bodies. This will be considered in an article following this one, as it goes too far afield to be introduced here.

All members of this little group of bodies are small compared with the four giant planets outside them, and yet they are large relative to the majority of satellites and planetoids. They form an intermediate group, and deductions respecting them may be checked by the extremes on either hand. Among themselves they form a graded series well suited to our purpose. The moon is distinctly small and has no appreciable atmosphere or hydrosphere; it may be taken to represent such bodies as are formed of molecules heavy enough and sluggish enough to be controlled by a limited attractive force, a force too feeble to hold the lighter and swifter order of molecules. Mars represents a stage of growth at which sufficient gravitative power has been reached to maintain a limited atmosphere and apparently the beginnings of a hydrosphere. Venus represents a much more advanced stage at which the gravitative power is sufficient to hold a very notable atmosphere and probably a rather massive hydrosphere. The earth, as we

well know, represents a stage at which a notable atmosphere and a distinctly massive hydrosphere have been acquired and held. The four bodies thus represent those stages of evolution which are most significant in such a study as this. They are all notably dense compared with the great planets that lie outside them and with the sun at the center of the system. The moon, Mars, and Venus will be treated as representing a typical series of stages of evolution connecting the small atmosphereless type with the largest known cold planet enveloped with a deep water-sphere and gas-sphere, the earth. No special study will be given to the large hot bodies of low density that form the great outer group.[1]

STATISTICAL DATA

Some of the more essential statistics on which the study will be based are gathered into Table I.

TABLE I*

Planet	Mean Diameter in Miles	Mass Earth=1	Density Water=1	Surface Gravity g=1
Moon.	2160 (3476 kms.)	0.0122	3.34	0.16
Mars.	4339 (6983 kms.)	0.1065	3.58	0.36
Venus.	7701 (12394 kms.)	0.807 (?)	4.85 (?)	0.85 (?)
Earth.	7918 (12743 kms.)	1.000	5.53	1.00

* These statistics are taken from Moulton's *Introduction to Astronomy*, Revised Edition, 1916. Venus has no satellite and its mass and density can only be determined by indirect means which are not very accurate, and hence the figures for these are marked with an interrogation point, but they are probably close enough for our purpose. The figure 5.53 for the density of the earth is conservative; figures as high as 5.56 and 5.57 have been used. These higher figures would give greater shrinkage. The dimensional data are given in miles and in kilometers, but the computations are carried out in miles, because, being the larger unit, it is the more convenient. An even larger unit is desirable for most earth studies and so the standard degree of a great circle of the earth is added in circumferential measurements. Degrees are convenient units in working with globes.

THE METHOD OF THE INQUIRY

As a step preparatory to the proposed comparison there were built up from the moon, Mars, and Venus, each in turn, by using material of its own mean density, parity-earths whose masses were equal in each case to that of the actual earth. A similar parity-earth was built up of mean meteoritic material. The radii and volumes of these parity-earths were then computed and taken as

[1] Cf. W. D. MacMillan, "On Stellar Evolution," *Astrophys. Jour.*, Vol. XLVIII, No. 1 (July, 1918), pp. 40–41.

the basis of shrinkage. The parity-earths were supposed to shrink until their mean densities were identical with that of the present earth. The amount of this shrinkage is recorded in Table II in terms (1) of the earth's radius in miles, (2) of the earth's circumference in miles, and (3) of the earth's circumference in degrees, each of these being more convenient than the other in certain specific uses.

In building up the meteorite earth Farrington's mean specific gravity of meteorites seen to fall was taken as the basis of computation.[1] While the inclusion of only those meteorites that have been seen to fall may not be strictly representative, it is Farrington's view that this limitation gives the best definite figure that is available. If the meteorites found but not seen to fall were included, the specific gravity would quite certainly be too high, because metallic meteorites are more likely to attract attention on account of their unusual heaviness and the whitish color of the metal, and because they are less liable to disintegration than the stony meteorites. Nevertheless, if all meteorites that have reached the ground in observable masses were averaged, the mean specific gravity would probably be greater than the figure given. On the other hand, the surfaces of iron meteorites are notably pitted, due probably to the exfoliation of the stony parts, as these are less tenacious than the metallic parts. A naked body sweeping about the sun and likely to be in rotation is quite sure to be subjected to those rapid changes of temperature which promote exfoliation. The gravitative power of a meteorite is very small and hence these exfoliated chips would be likely to be thrown off into separate paths and thereafter play the part of individual meteorites. It is thus probable that the vast multitude of small meteorites that are burned to dust in the upper atmosphere are much more largely stony than metallic. This consideration probably offsets any weight that ought to be given to the preponderance of metal among the meteorites found some time after their fall. At any rate the mean given by Farrington is the best available and is doubtless near enough the true mean to give the right order of magnitude to the results deduced from it.

[1] O. C. Farrington, *Jour. of Geol.*, V (1897), pp. 126–30.

While meteorites in the main seem to belong to the solar system, they appear to be samples from many sources, for they are extremely numerous and come to the earth from various directions and at very different velocities. It is therefore thought that they fairly represent the nature of any kind of scattered interplanetary matter of the solid type that might once have been available for the formation of small planets and satellites. This view does not rest so much upon their present status as upon the dynamics of the case, for the self-aggregation of small masses implies feeble gravitative control, and under the conditions of such feeble control only the heavier, sluggish molecules can be gathered and held. For this reason meteoritic material is taken to represent the densest type of scattered solid particles and small masses, whether planetesimal, satellitesimal, meteoritic, or otherwise, available now or in the past, for the growth of satellites and planets. This of course does not exclude the availability of lighter material, even gaseous material, to planets massive enough to hold such material, nor does it exclude occluded or combined gases from even the smallest bodies.

In building up these parity-earths, the series starts with the moon, the lowest in mean density, rises thence through Mars and the representative meteorite, to Venus, next to the earth in mean density, and ends with our planet. This arrangement should suggest at once that as the last two are the most massive bodies and hence have the greatest power of holding light molecules, they probably have the largest proportions of inherently light matter in their composition.

THE NUMERICAL RESULTS

The leading numerical results of the computations are gathered into Table II.

Let us hasten to admonish ourselves that these results are as yet uncriticized. Before the inquiry may properly rest these results must be scrutinized in the light of the dynamical conditions under which the four bodies were formed, for these conditions were such as to determine the inherent heaviness or the inherent lightness of the matter that formed them. This critical phase of the study will take us rather far afield and must therefore be deferred to a later article. I feel warranted, however, in saying that this further study will indicate, as does the hint given above, that the more massive

bodies in all probability contain the larger proportion of light atoms and molecules and that the shrinkage figures of Table II will need to be somewhat increased to satisfy the natural intimations of the laws of planetary organization. For the moment, however, let us regard these prospective increments merely as a measure of assurance that we will be forming first impressions on conservative grounds if we tentatively review the results as they stand. If this review shall raise any questions as to the validity of the results deduced these questions will serve to give piquancy to the deferred discussion.

TABLE II*

Basis of Parity-Earth	Density Water = 1	Present Radius	Present Volume Cubic Miles	Parity-Volume Cubic Miles	Parity-Radius Miles	Shortening of Parity-Radius Miles	Shortening of Parity-Circum. Miles	Shortening of Parity-Circum. Degrees
Moon	3.34	1080	5,276,678,626	430,353,000,000	4684	725	4555	66
Mars	3.58	2170	42,802,469,494	401,502,000,000	4577	618	3883	56
Meteorite	3.69	....	....	389,506,000,000	4531	572	3594	52
Venus	4.85	3851	239,226,992,649	296,367,000,000	4136	177	1112	16
Earth	5.53	3959	259,923,849,377	....	....	...	....	..

* The parity-earths may be derived either from the relative densities or the relative masses. The results, however, are not strictly identical in all cases, doubtless because the figures adopted are the weighted means of different methods of determining the masses and densities and these thus lose strict consistency with one another. The differences are not enough seriously to affect the order of magnitude of the shrinkage results.

PROVISIONAL DISCUSSION OF THE RESULTS

On first thought it may seem that the observed densities of the four bodies compared can be easily accounted for by assigning such specific gravities as are requisite to the material that entered into their formation. Thus the computed amounts of shrinkage may seem to be avoided. If it is legitimate to make purely arbitrary assignments in neglect of the laws of cosmic organization under such hypotheses of genesis as are tenable, no doubt this might be done. But in a naturalistic inquiry that tries to be thoroughly loyal to cosmic laws, so far as the inquirer knows them or can find them out, arbitrary assignments have little or no place. We are here dealing with highly composite results, the products of natural processes of organization. Each of the four bodies is believed to have been formed by a multitude of accessions brought together by forces of like types, acting under similar conditions and surrounded

by similar dynamic environment. It does not seem naturalistically probable that arbitrary variations of sufficient moment to affect the average order of results could have entered into these combinations so closely analogous in general nature. It is well recognized that under the law of probabilities a multitude of random contributions, uniting under common conditions, give closely concurrent averages even though the individual contributions may be highly variant. It will be seen from the discussion in the succeeding article that a very definite law probably presided over the proportion of the inherently heavy to the inherently light material which entered into the formation of the four bodies compared. Taking then their systematic organization for granted for the time being, the following tentative points are to be noted:

I. The total shrinkage of the earth implied by the comparisons is very large. A circumferential shrinkage of 4,555 miles in a putative growth from a moon stage by the addition of moon-stuff is certainly large. A similar shrinkage of 3,883 miles in a growth from a Mars stage by the addition of Mars-matter is quite as notable; and a shrinkage of 1,112 miles in a growth from a Venus stage—a stage in which 80 per cent of growth has already been attained, while the material added has the high density of Venus—is even more remarkable. These large shrinkages are ample to meet all the demands that gave rise to the inquiry and leave a good working margin beside.

II. Since the four bodies were treated as spheres, the computed shrinkages apply to all great circles, meridional, oblique, or equatorial, equally. The special deformations that may be assignable to changes in the rate of rotation are not here included. There was probably always some equatorial bulging and polar flattening, but the geological evidence does not seem to imply that deformations of this class were essentially greater during the early ages than they have been during the later ages.[1] The large shortening in meridional circles given by the computations satisfies the requirements of the Archean crumplings and related phenomena of the high latitudes, which seem to be essentially as great as those of low latitudes.[2]

[1] "The Tidal and Other Problems," *Publication No. 107*, Carnegie Institution of Washington (1909), p. 51.

[2] *Loc. cit.*

THE STAGE OF MAXIMUM SHRINKAGE

If the four bodies under comparison are to be regarded as representing stages of growth, it is a matter of much added interest to deduce from the comparison the stage of growth at which the greatest shrinkage took place. If the bodies were entirely compact at the outset, as they would be if fluid, or pliantly viscous, shrinkage from gravitative pressure might be expected to decline with every stage of compression reached, because resistance to compression usually increases rapidly as compression proceeds; but if the material of growth were minutely fragmental at the outset and the particles rigid and elastic, other factors of importance would come in. At first the porosity would be great. Until the porosity was exhausted the shrinkage would depend largely on the rigidity and the elastic qualities of the constituent particles. Later, the possibilities of chemical, crystalline, and physical readjustments in the interest of density would come into service. Another factor is the presence or absence of effective wash, solution, and redeposition. These are dependent on the presence or absence of an effective hydrosphere. The moon has neither appreciable atmosphere nor hydrosphere and if originally built up of minute rigid particles it would retain a deep porous zone of relatively low specific gravity. This would notably affect its mean density. Besides, there is evidence of much explosive eruption and the pyroclastic products arising from this would, in the absence of wash, solution, and redeposition, remain highly porous. The *Mare* once regarded as seas and later as lava plains may perhaps really be tracts of volcanic ash. Lines of projected débris crisscrossing *Mare Imbrium* are well shown in a recent photograph by the 100-inch reflector of Mount Wilson. Mars is on the ragged edge of doubt; it may perhaps have enough water on its surface to wash fine material from the exterior into the interior and to dissolve more or less of the surface material and deposit it in the pores below, or, on the other hand, the water may be so scant as to have little effect in cementing and solidifying the outer zone of the planet. But in the case of Venus, inwash and cementation are probably efficient, while they are known to be on the earth. All these factors seem to have played important parts in the results.

An inspection of the mean densities themselves gives some hint of the general nature of the compression: 3.34 for the moon, 3.58 for Mars, 3.69 for meteorites, 4.85 for Venus, and 5.53 for the earth. It is notable that the mean density of meteorites falls between the two bodies suspected of deep porosity and the two bodies in which wash, solution, and cementation are effective.

The results given in Table II bear an analogous import: 725 miles radial shrinkage for the lunar parity-earth; 618 miles for the Martian parity-earth; 572 miles for the meteorite parity-earth; and 177 miles for the Venus parity-earth. However, these shrinkages represent quite different ranges of growth; to be strictly comparable they must be reduced to a common basis. A convenient unit is an increase equal to 1 per cent of the mass of the earth. This is equal to the weight of about 14 billion cubic miles of water. Reducing the several shrinkages to this unit of mass increase, they become: for the mean rate of shrinkage between the moon stage and the mature earth, 7.44 radial miles per unit increase of mass; between the Mars stage and the mature earth, 6.90 radial miles per unit; and between the Venus stage and the mature earth, 9.17 miles per unit. This brings to attention the very suggestive fact that the rate of shrinkage per unit of mass increase *is greatest in the last stage*. Next to this, it is greatest in the growth from the stage represented by the moon, the body suspected of being the most porous, and the least affected by wash, solution, and cementation. The first seems to imply that massiveness is the dominant influence. Next to this porosity seems to be influential.

These inferences will appear to be still more strongly suggested if we reduce all the four natural bodies to parity-bodies, using mean meteoritic material as the basis. The results appear in Table III.

The third column shows that if the moon had been built up to its present mass with material of the mean density of meteorites, its radius would fall short of what it actually is by 35 miles; if Mars had been built up in a similar way its radius would be 22 miles short, while the radius of Venus built in the same way would be 367 miles greater than it actually is, and the radius of the earth under like conditions 572 miles greater than it is. If all these bodies were actually built up of mean meteoritic material the figures

would seem to mean that the porosity of the moon is represented by 35 miles in terms of radius, over and above such compression as its center has suffered. This may be taken tentatively as representing the deep porosity of the moon. Similarly, the porosity of Mars would be represented by 22 miles in excess of its central compression. On the other hand, the actual compression of Venus seems to be represented by 367 miles, while the corresponding figure for the earth is 572 miles.

TABLE III

COMPARISON OF METEORITE-PARITY WITH ACTUAL BODIES

Body	Radius Actual Body Miles	Radius Parity-Body Miles	Radii Differences Miles	Mass Units 1 Per Cent Earth Mass	Shrinkage Between Parity-Body and Actual Body per Unit=1 Per Cent Earth Mass Miles
Moon........	1080	1045	− 35	1.22	−28.7
Mars........	2170	2148	− 22	10.65	− 2.0
Venus........	3851	4218	+367	80.70(?)	+ 4.5
Earth........	3959	4531	+572	100.00	+ 5.7

In the fifth column the degrees of compression are reduced to a common unit-mass. This brings out the essence of the matter in a striking way. It appears that the moon, built up as it actually was, failed to compress itself to the meteorite standard by 28.7 miles per unit of mass-growth, and Mars by 2.0 miles per unit, while Venus compressed itself beyond the meteorite standard to the extent of 4.5 miles per unit of mass-growth, and the earth by 5.7 miles per unit. This seems to put the first two bodies in one category and the last two in quite another category, while it greatly emphasizes the progressive nature of the compression from the least to the greatest, even per unit-mass of increase.

Let us, however, hold all these tentative results in abeyance until we have more critically considered the probabilities in respect to the inherent nature of the material that entered into the constitution of these four bodies. Meanwhile this preliminary inspection may serve to give point to the study of the genetic conditions that affected these results. This study will be the theme of the succeeding article.

THE LAWS OF ELASTICO-VISCOUS FLOW. II[1]

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In a paper of Harold Jeffreys entitled "The Viscosity of the Earth"[2] the author makes use of a formula which combines the laws of Larmor and of Maxwell.

$$n(S+\tau_2\frac{ds}{dt}=F+\frac{1}{\tau_1}\int Fdt$$

The integral implies a permanent set which, as the author indicates, would be inconsistent with the "accepted theories of tidal friction and variation of latitude. Hence τ_1 must be practically infinite." The formula is thus reduced to the expression $F=n_1\ S+\tau_2\frac{ds}{dt}$.

Experiments made on a great variety of materials show, however, that this expression must be seriously modified to represent the facts.

Thus it has been shown[3] that the displacement produced by a stress P is given by the expression $S=C_1Pe^{h_1P}+C_2Pe^{h_2P}(1-e^{-\alpha\sqrt{t}})+C_3Pe^{h_3}t^{p}$.[4] The last term produces permanent set, so that for the present it may be omitted. Putting $C_1=\frac{1}{n_1}$ and $C_2=\frac{1}{n_2},\alpha=\frac{1}{\tau},\theta=\sqrt{t}$, this becomes

$$S=\frac{P}{n_1}\left[A_1+\frac{n_1A_2}{n_2}\left(1-e^{-\frac{\theta}{\tau}}\right)\right]\quad\text{whence}$$

$$n_1\left(S+\tau\frac{ds}{d\theta}\right)=P\left(A_1+\frac{n_1}{n_2}A_2\right).$$

[1] "The Laws of Elastico-Viscous Flow. I" appeared in *Jour. Geol.*, XXV (1917), pp. 405–10.

[2] *Monthly Notices of the Royal Astronomical Society*, LXXVII, No. 5.

[3] "The Laws of Elastico-Viscous Flow," *Jour. Geol.*, XXV (1917).

[4] The strains in these experiments were torsional, thus involving only the rigidity constant n. In the formula as given in the paper referred to the coefficients C and the exponents h are functions of the temperature. The stress P is constant and ρ is approximately one-half.

For small stresses $A_1 = A_2 = 1$, and if n_2 equal n_1 this expression takes a form resembling that given by Jeffreys.

It is important to note, however, that this formula is based on the assumption that the viscosity is "external," that is, it acts as though the viscous resistance were due to an absolute velocity $\frac{ds}{dt}$. But this is by no means evident; and indeed the probability is that a considerable part if not the major part of the viscous resistance may be "internal," that is, due to the relative motion of parts. Thus if an element consists of two parts y and z, y being coupled to the next adjacent element by an elastic coupling n_1 and with z by an elastic coupling n_2, together with a viscous coupling e_2, while e_1' and e_2' represent the "external" viscosities, the equations of motion will be

$$\rho_1 \ddot{z} = e_2(\dot{z} - \dot{y}) + n_2(z - y) + e_1'\dot{z}$$

$$\rho_2 \ddot{y} = e_2(\dot{z} -)\,\dot{y} + n_2(z - y) + e_2'\dot{y} + n_1\frac{d^2y}{dx^2}$$

If $\rho_2 e_1'$ and e_2' be considered negligible, the solution, for not too rapid extinction, is

$$z = ae^{-\beta x} \cos p(t - vx),$$

in which

$$v^2 = \frac{n_1}{\rho} \frac{(n_2 - \rho p^2)^2 + p^2e^2}{n_2(n_2 - \rho p^2) + p^2e^2}$$

$$\beta = \frac{\rho^{3/2} p^4 e}{2\sqrt{n_1}[n_2(n_2 - \rho p^2) + p^2e^2]}\,.$$

If pe is large compared with n_2

$$v^2 = \frac{n}{\rho}\left(1 + \frac{\rho^2 p^2}{e^2}\right)$$

$$\beta = \frac{\rho p^2}{2ev},$$

so that in this case the higher the viscosity the less rapid the decay of the oscillations—quite the reverse of the conclusions on the former

assumption. But the appearance of $\theta = \sqrt{t}$ is a more serious matter, making the use of the formula much more difficult.

The operator which should replace n is therefore

$$n_1 \frac{1+2\tau\sqrt{t}\frac{ds}{dt}}{1+\frac{n_1}{n_2}A_2}.$$

But the application of this formula to such a problem as the earth's viscosity is still further complicated by the fact that all the constants are functions of the pressure and of the temperature in the earth's interior. Even though more or less probable assumptions may be made regarding the value of temperature and pressure as functions of the distance from the center, we know but little regarding the effect of these factors on either rigidity or viscosity. It was found that the temperature effect may be represented with considerable accuracy by the expression

$$A = Ee^{(K+bP)\theta},$$

in which P is the applied stress, θ the temperature, and E, K, and b constants.

For room temperature the values of $b\theta = h$ are given in Table IV.

If we take $h_2 = 0.2$ as fairly representative

$$S_2 = Pe\,e^{.2P}(1-e^{-\sqrt{t}}).$$

The unit $P = 100$ gm., so that G the couple $= Pr$ gm. cm. Thus we get for the displacement, after a sufficiently long time,

$$S = Pe\,e^{.2P} \text{ and } \frac{1}{n_2} = \frac{S}{P}.$$

Table I shows the very great increase in importance of the elastico-viscous term for large stresses. The same is also true for the purely viscous term.

TABLE I

P	=	S/P
0		1
1		1.2
10		7.
50		20,000.

Table II gives the ratio $\frac{n_2}{n_1}$ for twenty-two materials, showing that there are certainly two elasticities, one of which is not accompanied by viscosity and the second is thus affected. In every case excepting that of sealing wax, where the ratio is unity, the second elasticity is much greater than the first, and in some cases enormously greater.

TABLE II

	$\frac{n_2}{n_1}$		$\frac{n_2}{n_1}$
Tin	60	Slate	150
Zinc	70	Shale	50
Marble	45	Soapstone	35
Limestone	30	Lead	40
Ebonite	8	Cadmium	65
Iron	2,200	Gold	150
Steel	12,000	Magnesium	250
Copper	8	Bapelite	7
Aluminum	4,400	Ivory	50
Talc	200	Silver	80
Glass	100	Sealing wax	1

The introduction of $\sqrt{t}$ instead of t itself is a step so radical that it may be well to give an illustration in its justification. For this purpose it is desirable to choose a material in which the elastico-viscous effect is well marked. This is notably the case for vulcanite, which has the added advantage of the relatively small importance of the third or purely viscous term. This illustration is perhaps the most striking in showing the appropriateness of $\sqrt{t}$ instead of t; but all the materials investigated give similar results.

Table III is a table of results for R_0, the return at the time t after releasing the stress.[1] $R_{\sqrt{t}}$ gives the result of calculation from

$$R=890(1-e^{-.57\sqrt{t}}) .$$

R_t gives values calculated from

$$R=840(1-e^{-.4t}) .$$

The differences between calculated and observed values under Δ_1 and Δ_2 show that the former expression is very near the truth, while the latter is entirely inadequate.

TABLE III

t	R_0	$R_{\sqrt{t}}$	Δ_1	R_t	Δ_2
1..........	380	387	7	277	−103
2..........	490	492	2	462	− 28
4..........	600	605	5	672	+ 72
9..........	730	729	−1	820	+ 90
16..........	800	802	2	838	+ 38
25..........	840	841	1	840	00
30..........	853	851	−2	840	− 13
∞..........	890	890	0	840	− 50

While the term involving a permanent set may not have any application to the problem of the earth tides, yet it may not be amiss to draw attention to the fact that in some cases and especially at temperatures approaching the melting-point, this term becomes the most important of all. The temperature coefficient in this case enters in the form $\theta/T-\theta$, giving as it should perfect fluidity at T, the melting-point.

In the former article the expression given for this viscous term is $S_3=(Ft)^p$, in which $F=C_3Pe^{h_3P}$ and p is stated to be approximately one-half.

From more recent data the average value of p is .41; and if from the nineteen substances examined four be excluded the average is .35, which makes it much nearer one-third than one-half.

[1] It was found by experiment that for stresses not too great the "direct" curve (on applying the stress) and the "return" curve (on releasing) were the same; or rather if the former is S and the latter R, then $S+R=Ct$.

TABLE IV

	C_1	C_2	C_3	C_4	h_1	h_2	h_3	h_4	α	ρ
Tin slowly cooled	660	20.	3.0	1.0	.10	1.0	3.5	4.5	0.8	0.6
Tin quickly cooled	640	8.	0.6	0.3	.00	1.8	3.8	4.6	0.8	0.6
Zinc slowly cooled	312	3.	3.4	2.0	.00	0.4	0.3	0.8	1.0	0.5
Zinc quickly cooled	300	8.4	3.0	.00	.00	0.4	0.6	1.8	1.0	0.5
Marble	840	18.	40.	34.	.14	1.8	0.8	0.3	1.1	0.2
Limestone	600	20.	9.	11.	.10	0.3	0.3	0.8	1.2	0.3
Ebonite first determ	13×10^3	1600.	600?	0?	.00	0.1	0.0	....	0.6	0.5
Ebonite second determ	13×10^3	1800.	750.	.00	.00	0.1	0.2	....	0.9	0.7
Soft iron annealed	145	.06	.00	.15	.00	0.1	....	0.1	1.0	0.2
Soft iron unannealed	155	.08	.00	.15	.04	0.1	....	0.1	1.0	0.2
Tool steel annealed	144	.01	.00	.10	.00	0.2	....	0.1	0.4	0.3
Tool steel glass hard	143	.14	.26	.07	.00	.00	.03	.06	0.4	0.4
Copper annealed	250	1.3	.00	.75	.06	0.1	1.8	1.2	0.5	0.3
Aluminum annealed	440	0.1	.00	.9	.00	1.0	2.5	1.4	1.0	0.3
Talc parallel cleavage	1340	4.0	20.	110.00	.60	3.0	1.4	1.2	1.0	0.3
Slate parallel cleavage	382	2.0	0.4	0.6	.01	0.3	0.7	0.6	1.2	0.3
Slate perpendicular to cleavage	400	4.0	1.6	1.0	.03	0.3	.00	0.8	1.5	0.6
Sealing wax	3×10^4	2×10^4	?	?	.00	.00	.00	.00	0.7	?
Glass (plate)	446	3.0	.00	4.0	.00	.00	.00	.00	0.5	....
Glass (lead)	425	5.6	.00	0.1	.00	.00	.00	.15	1.4	....
Shale parallel cleavage	400	8.4	1.0	1.2	.02	.16	.35	0.6	1.2	0.4
Lead	1500	40.	7.	4.	.00	0.2	1.9	3.6	1.1	0.4
Cadmium	460	70.	5.4	2.4	.00	0.2	0.6	0.8	1.0	0.5
Gold	450	3.	0.2	1.0	.00	.04	0.2	0.3	1.0	0.3
Magnesium	2300	9.4	8.	50.	.00	.25	0.4	0.6	1.2	0.3
Bakellite	7400	960.	14.	.00	.00	.12	0.2	....	1.2	0.8
Ivory	10^4	320.	3.	.00	.00	.10	0.2	....	0.8	0.6
Silver	480	6.	2.	0.4	.00	.06	0.1	0.2	1.0	0.3

The expression for the viscous term should be $S_3=(Ft)^{\frac{1}{3}}$ if the stress (P) is constant. If P is a function of time

$$S_3=(\int F dt)^{\frac{1}{3}}\,.$$

Thus if P be given a constant value for a time t_0 and then changed to P_1 the corresponding value of the viscous term would be

$$S_3=(F_0\,t_0-F_1 t)^{\frac{1}{3}}\,.$$

If the first stress be considerable and act for a long time the effect of the second stress is negligible.

Table IV is a provisional table of the constants which appear in the formula for the torsional strain at room temperature.

$$S=A_1+A_2(1-e^{-a\sqrt{t}})+A_3 t^p+A_4,$$

in which $A=CPe^{hP}$. P is the weight acting on a pulley of radius 5 cm., the unit of weight being 100 gms. and the unit of time one minute. The specimen is a cylindrical rod 7.5 cm. long and 4 mm. in diameter.

The term A_4, which may be termed the "lost motion," should probably be considered as a part of the viscous term, but with a very small exponent r, so that the whole viscous term may be represented by

$$S_3=C_3Pe^{h_3P}(t^p+Bt^r)\,.$$

THE GREAT GLASS-SPONGE COLONIES OF THE DEVONIAN; THEIR ORIGIN, RISE, AND DISAPPEARANCE

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A very striking feature of the biota of the Devonian as represented in the state of New York is the extraordinary development in its late stage, the Chemung period, of its silicious hexactinellid sponges. At various levels in the sandy deposits of this time they are found, sometimes as scattered individuals and sometimes in plantations of uncounted numbers, so that it is safe to say that from the bottom of the formation in the "southern tier" of counties to near its summit, the hexactinellids of this order, the Dictyospongida, are many times more abundantly represented than in all the rest of the world together. In their extensive monograph of these sponges Hall and Clarke ascribe seventy-seven species in sixteen genera to this formation within the borders of New York and the same rocks in northern Pennsylvania. Clarke has described a number of additional Chemung species, so that there are now about ninety outstanding specific designations for this Devonian assemblage.

Sometime it will be a subject for discussion among morphologists whether this so-called order, Dictyospongida, is homogeneously constituted; probably it is not, but so seldom is the spicular structure retained in the sandy matrix that on the basis of general form and habit, and the arrangement of the spicular bands which are usually sharply preserved in impressions, all the sponge occurrences in this formation and those of like composition in the Mississippian faunas of Ohio and Indiana are now for convenience put in this single group. That they are for the most part accurately referred to the hexactinellids is abundantly shown by the spicular structure of the Mississippian species which has been demonstrated. The described species and genera have been established with the best

knowledge available; more exact determinations must await better preserved materials.

AREA OF OCCURRENCE

The area of deposition in which these Devonian hexactinellids are most prolific is quite distinctly limited along the line of outcrop in the region running from Cattaraugus County on the west to Otsego County on the east, about 150 miles; they accompany the area of most typical sandy sediment. As soon as the formation begins to lose in sand in its extension westward and to the east the sponges disappear.

NUMBER AND NATURE OF COLONIES

While scattered individuals and groups of sponges occur at random through these rocks and add much to the variety of the fauna, it is the great plantations or colonies that are here the subject of special reference. It is probable that we know as yet but few of the colonies that once existed. Some have been irreparably lost and doubtless others await discovery. But we may here take note of the following:

1. *The Hamlin Farm Colony*, Naples, Ontario County.—This lies nearest the base of the formation and is the oldest of all the colonies known. It appears to have been entirely composed of the species *Hydnoceras tuberosum* Conrad, of the tuberous or "alligator tail" type. Some hundreds of specimens have been found here.

2. *The Brown Hill Colony*, near Avoca, Steuben County.—Here again *Hydnoceras tuberosum*, the type of the genus and the first of all the dictyosponges to be described, is the prevailing if not the exclusive form. Wagonloads of these sponges have been taken from this place.

3. *The Jenks Quarry Colony*, near Bath, Steuben County.—The sponges here are also of the tuberous type but belong to the species *H. bathense*, H. & C., with an occasional representative of *H. botroedema* H. & C. This is the largest of all the assemblages. Workmen in the quarry, 30 years ago, found a layer of sandstone with a "curly grain" running through it that made it unfit for their

market and it was thrown out on the spoil bank. The discarded blocks came to the attention of the state's geologists and a carload of the layer was specially quarried for them. One slab of this layer, 8′×4′, now exposed in the State Museum, carries about 250 sponges lying as they were left, knocked over on their sides by some heavy tide. The carload of sponges contained probably not less than 5,000 individuals. The layer carrying them extended over the full face of the quarry, 120 feet, and indefinitely inward. The census of the colony cannot be estimated except in very large figures of tens of thousands.

4. *The Irish Hill Colony*, near Bath.—This is known only by the multitude of specimens of *H. botroedema* found loose in the soil at this place.

5. *The Halli Colony at Wellsville*, Allegany County.—Here the horizon is high in the formation and the species is *Thysanodictya Edwin-Halli* H., of which several hundred specimens were found by the late E. B. Hall, of Wellsville.

PREVIOUS HISTORY OF THE DICTYOSPONGIDA

Limiting the term to the characteristic expressions of the Devonian and Mississippian, they have little record of previous history; there is a single doubtful specimen from the mud beds of the Hamilton shales (*Clathrospongia ? hamiltonensis* Hall) and some hexactin patches in the black Marcellus shale, *D. ? marcellia* Clarke. Fragments of like type, but heretofore unrecorded, have been found in the Rochester shale of New York. In this statement we are eliminating from the group the Cyathospongia forms of the Utica shale, the Levis beds of Little Metis (Ordovician), and the extensive assemblage of similar hexactinellids in the Cambrian, especially those found by Walcott but not yet described. It is proper to exclude these even though they may have full ordinal relation with the Devonian species, because of the vast vacant interval of time between the earlier and later records. There were species of these sponges in the upper beds of the Portage group (three of Hydnoceras, one of Prismodictya, one of Dictyospongia, and one of Clepsydrospongia), but they must be regarded as

belonging to the advance guard of the Chemung army, as in various respects the faunal relations of the two are close.

HABITAT OF THE DEVONIAN SPONGES

These glass sponges obviously grew on sandy bottom at a depth which could not well have been more than one hundred fathoms, and probably not more than fifty. The waters of the epicontinental seas were always shallow; even the clay and lime muds betoken no depth comparable to the deep-sea oozes and blue muds of the present oceans. There is no single exception to this interpretation that could carry any weight in the presence of such overwhelming proof of the adaptation of this great array to conditions of life wholly unlike those under which their successors are living. When the Devonian time was over the simpler and typical expressions of the obconical, prismatic, and nodose sponges disappeared and were replaced by accelerated species of like stock (twenty species are recorded by Hall and Clarke) in the Mississippian stage, the Waverly and Keokuk divisions, in which there is a notable increase of lime sedimentation and consequent evidence of a deepening sea.

HABITAT OF LIVING HEXACTINELLIDS

Depth habitat.—Generally and specifically, these are deep-sea animals. Agassiz dredged them from 2,410 fathoms, but the "Challenger" expedition, as shown in Schulze's report, determined a greater range and a greater depth. The "Challenger" garnered about one hundred species, none of which grew at less than ninety-five fathoms. The summary of the record is as follows:

From	95 to 200 fathoms	24 species
	200 to 300 fathoms	none
	301 to 700 fathoms	35 species
	701 to 900 fathoms	none
	901 to 1,000 fathoms	2 species
	1,001 to 2,900 fathoms	47 species

Thus all the species are of the deeps and many of the very great depths.

Ground habitat.—The nature of the ground determined for 101 of these species is given by Schulze as follows:

Material	Number of Species
Sand	5
Gravel and stones	2
Hard ground	6
Coral mud	7
Volcanic mud	14
Green mud	1
Red mud	2
Mud (including blue mud)	32
Red clay	11
Globigerina ooze	13
Pteropod ooze	7
Radiolarian ooze	2
Diatom ooze	9

Schulze observes that forms equipped with root tufts were principally found in soft muddy ground, and in the Devonian seas the species generally were provided with a more or less conspicuous tuft of this kind.

Temperature habitat.—The temperature of the Chemung period was probably pretty cool. Glacial ice had formed over the elevated land of the middle Devonian on the Atlantic border of this continent and now with partial resubmergence the refrigerated waters were discharging themselves, with abundant landwash, into the shallow seas. In the Portage division of the late Devonian an immigrating warm water fauna (the *Manticoceras intumescens* fauna) coming in from the west was blocked and stopped on its way, driven out or destroyed by the presence of the cool waters carrying the Chemung fauna.

Today the hexactinellids show an apparently different temperature control, as witness the "Challenger's" record:

North Temperate zone	20 species
Tropics	45 species
South Temperate zone	35 species

This apparent difference is compensated by the cold of the deep waters.

RELATIVE ABUNDANCE OF LIVING AND DEVONIAN SPECIES

Continuing to use the "Challenger" reports we find a contrast in the abundance of individuals growing in any one place, but in making this comparison we must remember that the zoölogist is dipping into the sea bottom with a rake on the end of a string, while the paleontologist is on the sea bottom itself, with dynamite, crowbar, and hammer. The "Challenger's" dredgings rarely found any considerable number of individuals at any one place; "generally only one or two specimens of each species were obtained at the same locality. Sometimes, however, a considerable number of specimens were found at once." None of this evidence seems to point toward colonies or plantations in such vast numbers as in the Devonian. Today the strongholds of the hexactinellids are about the Philippines, Little Ki and Kermadoc islands; in the deeps of the southern Indian Ocean between Prince Edward and Crozet islands; and in Atlantic waters, off the Bermudas and St. Thomas.

ONTOGENY OF THE DEVONIAN SPONGES AS AN INDEX OF THEIR ADVANCED AGE AND SPECIALIZATION

There are four simple types of morphology, contemporaneous and combined, among the Devonian dictyosponges: (1) the smooth obcone, regularly expanding like a cornucopia and gently contracting about the open aperture; (2) a six-sided prismatic or banana shape; (3) a subprismatic obcone with successive transverse rows of tufted nodes, typically eight to a row; (4) long obcones with concentric rings, like the horn of an Oryx. These simple expressions have a successive value in ontogeny.

The first group constitutes the genus *Dictyospongia*. The second, in its typical expression, is the genus *Prismodictya;* but in several species not included in that genus the prismatic phase is superinduced upon and subsequent to the smooth phase. In other genera or species the later growth of the prism may show a tendency to develop nodes at the prism angles. *Hydnoceras* is the name applied to the typical tuberous or nodose forms and *Ceratodictya* expresses the annulated phase. These different expressions are, as just observed, essentially successive in the chronologic order of

ontogeny. In a progressed species the preliminary phases may be reduced by acceleration and even suppression but they are usually determinable; that is, a species of Hydnoceras (cf. *H. Walcotti*

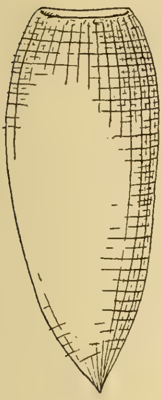

FIG. 1

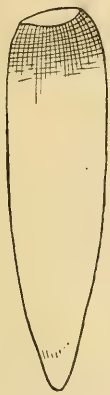

FIG. 2

FIG. 3

FIG. 4

FIG. 5

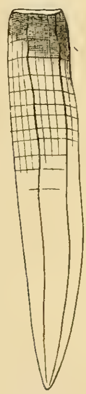

FIG. 6

FIG. 7

FIGS. 1–3.—The typical or radicle form as expressed by (1) Cyathodictya and (2, 3) Dicyospongia.

FIG. 4.—The development of the Prismodictya faces.

FIGS. 5–7.—The Prismodictya type with inception of Hydnoceras tufts.

Clarke) will show over its initial surface, first the smooth and then the prismatic and tufted development, and even in its mature and final expression, decided development of the concentric rings.

These features of ontogeny are brought out for a number of species in the accompanying figures.

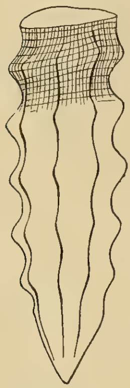

FIG. 8

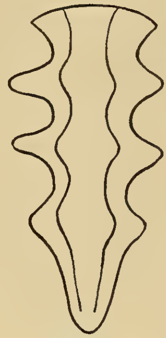

FIG. 9

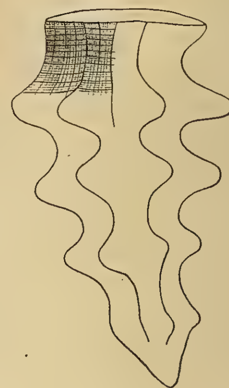

FIG. 10

FIG. 11

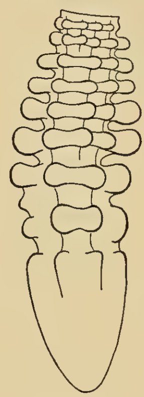

FIG. 12

FIG. 13

FIGS. 8–11.—Various expressions of the Hydnoceras tufted type in which the Prismodictya and the earlier Dictyospongia stages are indicated.

FIG. 12.—Hydnoceras Walcotti; an extreme expression of this combination, showing notable retention of the Dictyospongia stage, union of the prismatic and tufted stages, and the development of the annulated condition.

FIG. 13.—Botryodictya, a condition in which the Dictyospongia stage is protracted and abruptly develops into a cup-shaped, tufted, and pouched condition.

In many species ontogenetic development is carried into extremes of nodosity and annulation, resulting, especially in later species, in great variability of form even within the confines of the Devonian.

Enough however has been given to indicate the degree of morphologic specialization displayed by these hexactinellids in the

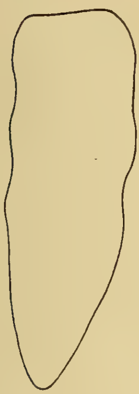

FIG. 14

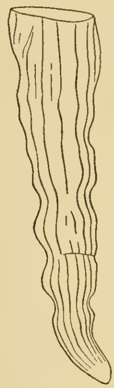

FIG. 15

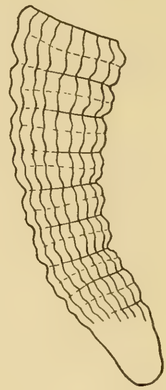

FIG. 16

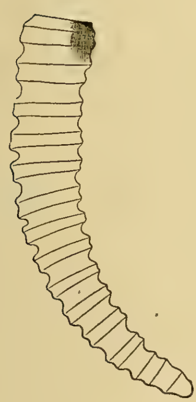

FIG. 17

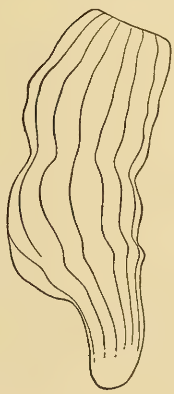

FIG. 18

FIG. 19

FIG. 14.—The incipient annulated or Ceratodictya stage.

FIG. 15.—The annulated stage combined with an extreme expression of the prismatic form (Rhabdosispongia).

FIGS. 16, 17.—Phases of the Ceratodictya stage, Hydnocerina (16), showing departure from the type.

FIGS. 18, 19.—Expressions of two of these phases (Rhabdosispongia and Hydnoceras) from the Frasnian formation of France.

Devonian, a condition which must have required ages of time to work out. The Devonian sponge colonies must therefore have had a vast ancestry.

WHERE DO THESE DEVONIAN SPONGES COME FROM AND WHAT WAS THEIR ANCESTRY?

The answer to the first query may take this form: Between the species in the dark shale of the early Ordovician (Levis shales) and this invasion in the late Devonian, there is but a single recorded species which would seem safely placed among the Dictyosponges, viz., *Dictyospongia danbyi* McCoy from the Upper Ludlow (Silurian) of Westmoreland. We have referred to a similar occurrence in the Silurian of New York. It is quite possible that these were but derelicts tossed shoreward. The striking hexactinellids described by Dawson from the Levis shales seem to have for the most part the simple obconical foundation with special developments of spicular tufts which indicate that up to this time there had been no wide departure from the simple type of *Cyathospongia* which is repeated in the genus *Dictyospongia*. The other differentials of the Dictyospongida do not appear.[1]

The dark shales in which those early species (Ordovician and Cambrian) are preserved indicate a greater depth of water than do the Devonian colonies. We may therefore think of them as having invaded the deeper epicontinental seas from the much deeper waters of the continental edge at a time when the way was freely open to the margins of the platform. If they were traveling in toward ever-shallowing water there would or should be remains of them in the black shales and the sands of the interval deposits. There are none, and the fact constrains us to think that, instead of traveling into shallow waters, they were moving back to the deeper waters, where, concealed from the accessible rock records, they were working out their evolution. Then some impulse which may not be defined[2] drove them into the shallow epicontinental waters,

[1] It is presumed, but not proven, that these early hexactinellids were Lyssacine, that is, had the parenchymous tissue filled with detached spicules as contrasted to the fused parenchymalia of the Dictyonina.

[2] Austin H. Clark, writing of causes of marine migrations, says: "*Internal specific pressure* due to enormous increase in the number of individuals within a species operates not only to cause a species to colonize bathymetrically undesirable locations or unnaturally cold and uncongenial regions such as the polar seas but also to force species into small localized areas." (Quoted by Ruedemann, *Paleontology of Arrested Evolution*, p. 128, 1918.)

clothed in their new differentials. No shallowing of the sea or positive diastrophy is required for this explanation. By the time the Chemung outburst of species was effective all egress to or access from deep water was shut off. Examination of Schuchert's paleogeographic maps of this time will bring out this condition clearly. There was no deep-water Devonian in the vicinity at that period; to the east and south lay the Appalachian lands; to the north Laurentia, and on the west a long and, we must say, putative channel reaching in from the Pacific border. Through this channel the sponges may have gone out.

We conclude that the long evolution of these sponges from their appearance in the dark Cambrian and Ordovician muds to their immigration in the late Devonian was passed in the deeper waters of the continental edge and is recorded in sediments beyond the present reach of our observation.

Barrois discovered the Dictyosponges in the Psammites du Condroz of Jeumont in Brittany in sandy sediment at a horizon equivalent to the Chemung of New York, and four of these species in three genera were described and illustrated by Hall and Clarke (*op. cit.*). This is interesting collateral evidence of the widespread influence which in the Northern Hemisphere impelled these sponges on to the platform seas.

WHY AND WHERE DID THE CHEMUNG DICTYOSPONGES GO?

The course of their ontogenetic development shows that their later expression assumed gerontic and adaptive characters in great variety. The stratigraphic record indicates that the sandy bottom on which the New York colonies and their contemporaneous species grew was overwhelmed by incursions of coarse gravel washed in from the rivers of the eastern Appalachian land. These terminated their local existence and the Devonian period as well. Their emigration from southern New York was westward and into deeper waters of the Waverly group of western Pennsylvania and Ohio and the Keokuk lime muds of Indiana. In these Mississippian sediments they make their last appearance. But they were on their way down to deeper waters and we find no reason against the assumption that it was the westward course they followed on to

the epicontinental margin. As Dictyosponges they have never reappeared, nor as Lyssacine hexactinellids. That rôle was played. When their successors came back in the Jurassic and Cretaceous times their independent spicules had been fused into continuous networks and, as Dictyonine sponges, they carried on their important work as reef and rock builders. Seldom, however, did they reproduce the form of their Devonian predecessors; indeed the ancient form is far better revived in the glass sponges of today. That, too, is an interesting illustration of once more passing the same point on the cycle of their development history.

SUMMARY

1. In the Cambrian and Ordovician times the Lyssacine hexactinellids grew freely in the black muds of moderately deep epicontinental waters.

2. They were on their way off the American continental platform and down to the marginal seas.

3. Here they carried out their evolution during the long Silurian (when a stray species came ashore) and all the early stages of the Devonian.

4. In the later Devonian they return in great force and with their evolution fully under way, but not to such an extent as to conceal their ontogenetic stages and the radicle expression on which they were based. To this reappearance on the epicontinent they were evidently impelled by some *vis a tergo*, some compelling *external* force, probably the invasion of their province by a dominating life-element of another kind. They were caught in a general migration of the time into the shallow and cool waters of the Chemung, and in these waters they perfected their evolution.

5. Out of these shallow waters they were driven by an incursion of fresh waters which flooded the Devonian province with gravel from the eastern lands.

6. They migrated thence westward into the deeper waters of the Mississippian and from there once more to the circumcontinental seas.

7. In their return to the epicontinents of the Jurassic and Cretaceous their development had advanced to a change of skeletal structure and a wide variation of form.

8. Their departure from the Mesozoic epicontinents came with the opening of the Tertiary. They have never returned to epicontinental waters.

9. Today their descendants present a wide vertical range in the ocean waters, indeed an extraordinary adaptation through 2,800 fathoms. The deepest water forms are hopelessly isolated—they cannot climb the hill back to the zones of evolution and they will be as they are for future generations of observers. It looks as though all of them were traveling down to the depths; in which case the race will become stabilized and "immortal."

10. The history then is one of cycles of migration and development, of compelling impulses governing the former and probably inducing the latter.

A QUANTITATIVE MINERALOGICAL CLASSIFICATION OF IGNEOUS ROCKS—REVISED

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PART I

In response to a request published in a former paper on a quantitative mineralogical classification of igneous rocks,[1] numerous letters have been received from petrographers in this country and abroad. Practically no objections were raised except against the separation of the feldspar molecules. With this separation the writer himself was not fully satisfied, and he reverted, shortly after the paper was published, to the subdivisions used by him when the classification was first presented to his students some nine years ago, namely, that of dividing the feldspars simply into plagioclase, on the one hand, and the remaining feldspars, on the other. In the following article this change is shown. A further modification is introduced in Class 4, although no objection was made to it as previously given. The new subdivisions are somewhat simpler than before.

An extensive change, embracing the omission of the 72 families of the monzonite series (Fig. 1), was contemplated, and personal letters were sent to a considerable number of petrographers asking opinions. Unfortunately the answers were so far apart that it has seemed best to allow the divisions to remain as they were. The need of more uniformity in classification was brought out clearly by the replies to this one question, as a comparison of the granite quartz-diorite series of several petrographers will show (Fig. 2).

Essentially the system now is as follows. For a detailed description the reader is referred to the former paper.

Classes.—On the basis of the amount of dark minerals (mafites) present, the igneous rocks are divided into four classes, the division points being 0–5–50–95–100 per cent mafites.

[1] Albert Johannsen, "Suggestions for a Quantitative Mineralogical Classification of Igneous Rocks," *Jour. Geol.*, XXV (1917), 63–97. In that paper delete *eudialyte*, p. 90, l. 15, and change *less* to *more* under Class 1, p. 91, l. 26.

Orders.—Each of the first three classes is divided into orders (Fig. 3) according to the Ab–An ratio in the plagioclase. The division points are $Ab_{100}Ab_0$, $Ab_{95}An_5$, $Ab_{50}An_{50}$, $Ab_5\,An_{95}$, Ab_0An_{100}. There are thus formed, for each class, four double triangles (Fig. 4), in each of which three angles represent (1) quartz (Qu), (2) all feldspars except plagioclase (Kf), and (3) the feldspathoids (Foids).

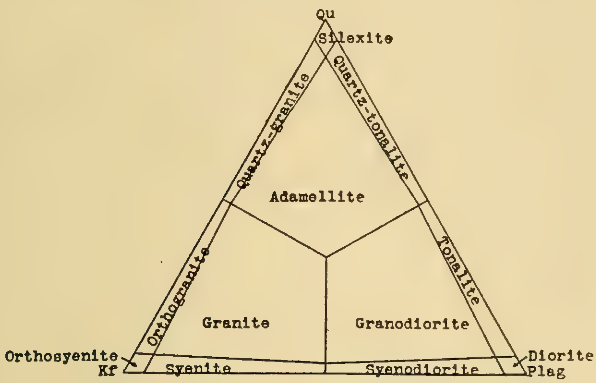

FIG. 1.—A proposed change in family divisions

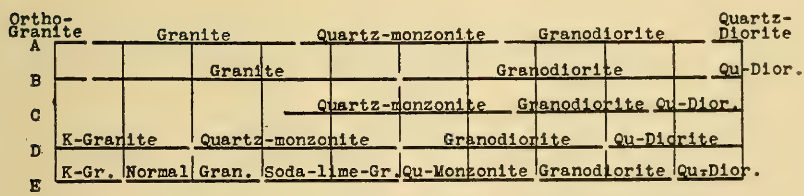

FIG. 2.—Variations in the usage of names in the granite quartz-diorite series: *A*, divisions used in the present classification; *B*, divisions suggested (cf. Fig. 1); *C*, Lindgren's original divisions; *D* and *E*, divisions as used by certain other petrographers. The right ordinate is orthoclase, the left, plagioclase.

The remaining angle (Plag) represents albite (Naf), oligoclase to andesine (Ca*Na*f), labradorite to bytownite (Na*Ca*f), or anorthite (Caf), and these constitute the basis for the separation into Orders 1, 2, 3, and 4.

In Class 4, owing to the absence of light constituents, it is necessary to make the subdivisions on a different basis. In this class,

therefore, each order represents an increased amount of the "ores" (Fig. 5). The division points, as in the other case, are 0–5–50–95–100.

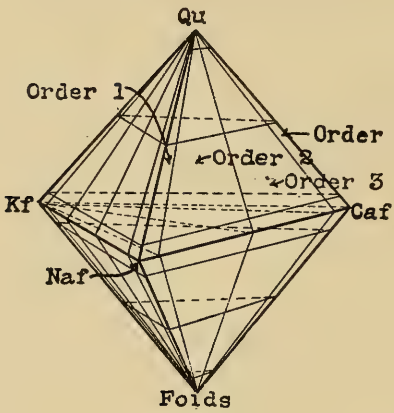

Fig. 3.—Subdivisions of the tetrahedron into orders.

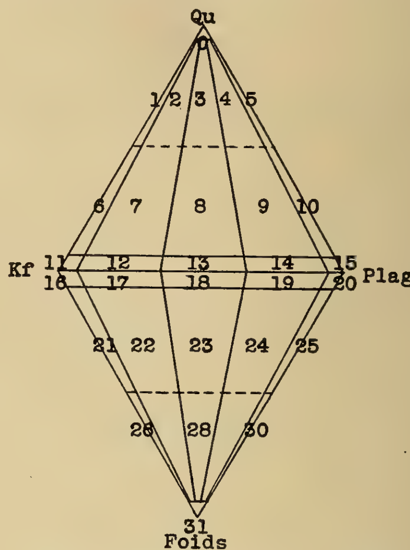

Fig. 4.—Family divisions in Classes 1 to 3.

Families.—Finally, each order is subdivided into families. In Classes 1, 2, and 3, the divisions, as shown in Figure 4, are at 0–5–35–65–95–100 on the feldspar base line, and at 0–5–50–95–100 from this line up or down toward quartz or the feldspathoids. Families 0, 1, 6, 11, 16, 21, 26, and 31 occur only once in each class (cf. Fig. 3), since the amount of plagioclase in each, whether it be albite, acid plagioclase, basic plagioclase, or anorthite, is too small to make an essential difference in the rock. These "hinge families" are classed, for convenience, in Order 1.

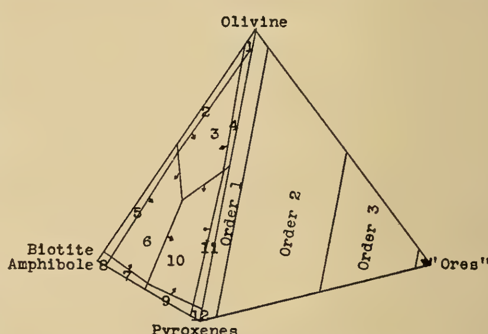

Fig. 5.—Orders and families in Class 4

In Class 4 the orders are subdivided as in Figure 5. The families are numbered from 1 to 12, as shown, and are divided at 0–5–50–

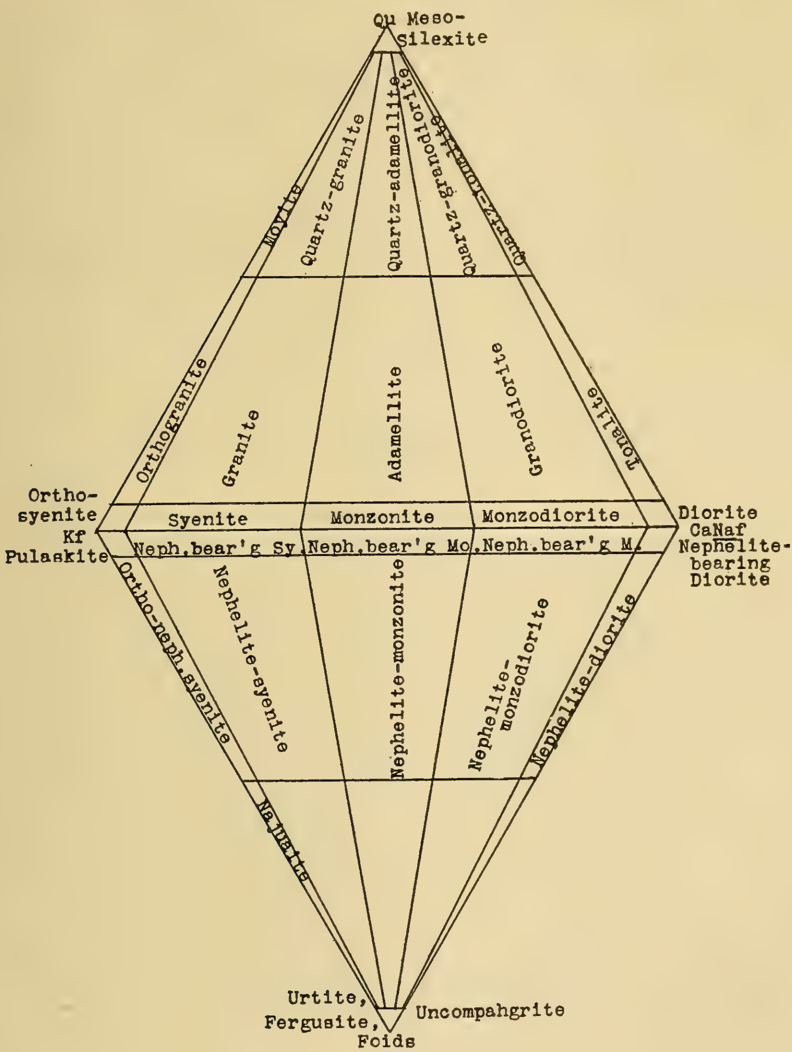

FIG. 6.—Families in Class 2, Order 2

95–100. The three corners, in Orders 1, 2, and 3, represent respectively olivine, biotite and (or) amphibole, and the pyroxenes. In Order 4, if thought desirable, the corners may be taken to

represent the various ores; the writer, however, groups the ores in one family, for, considered as rocks, they are unimportant and hardly worth separating.

THE MINERAL GROUPS

The constituents of the rock are divided into three primary groups:

QUARFELOIDS

(Qu)	Quartz
(Kf)	Orthoclase, microcline, microperthite, anorthoclase, etc.
(Plag)	The whole isomorphous Ab–An series of plagioclases
(Foids)	The feldspathoids (nephelite, leucite, sodalite, hauynite, noselite, melilite, primary analcite, etc.)

MAFITES

Dark micas (biotite, phlogopite, etc.)
Amphiboles
Pyroxenes (including uralitized pyroxene)
Olivine
Iron "ores" (magnetite, ilmenite, chromite, pyrite, hematite, etc.)
Cassiterite

Minor Mafites	Garnet Primary epidote Allanite, zircon, rutile, primary titanite, spinel, and other dark minor constituents

AUXILIARY CONSTITUENTS

The auxiliary constituents are seldom of importance.

Topaz	Primary scapolite
Tourmaline	Primary calcite
Cordierite	Muscovite
Corundum	Lepidolite
Fluorite	Zinnwaldite
Andalusite	Apatite, etc.

Most of the auxiliary constituents are light in color; they are, consequently, computed among the leucocrates.

SECONDARY CONSTITUENTS

Secondary constituents are to be calculated as the originals from which they came. Thus ore replacements of the mafites are computed as mafites, kaolin as feldspar, etc., chlorite as a biopyribole, analcite as feldspathoid, pseudoleucite as leucite, etc.

GLASS

Glass must be computed from an analysis. One can usually surmise its composition from the character of the phenocrysts and the appearance of the rock as a whole. When undetermined, the rock must be given a tentative name, such as hyaline-rhyolite, etc.

RULES FOR COMPUTING ROCKS FROM THEIR MODES

1. The sum of the minerals in the mode should be 100 ± 0.5. If less it should be recalculated to 100. The sum of the leucocrates (quarfeloids plus auxiliary minerals) determines the class.

Class 1. Leucocrates form more than 95 per cent of the total component.
Class 2. Leucocrates between 95 (inclusive) and 50 per cent.
Class 3. Leucocrates between 50 (inclusive) and 5 per cent.
Class 4. Leucocrates between 5 (inclusive) and 0 per cent.

2. Determine the orders in Classes 1, 2, and 3 directly from the Ab–An ratio in the plagioclase.

Order 1. $Ab_{100}An_0$ to $Ab_{95}An_5$.
Order 2. $Ab_{95}An_5$ (inclusive) to $Ab_{50}An_{50}$.
Order 3. $Ab_{50}An_{50}$ (inclusive) to Ab_5An_{95}.
Order 4. Ab_5An_{95} (inclusive) to Ab_0An_{100}.

In Class 4 the orders are determined by the percentage of "ores." Reduce the sum of biotite, olivine, pyribole, and "ores" (including cassiterite, chromite, etc.) to 100, dropping the minor mafites, apatite, garnet, perofskite, any small amount of quarfeloids, etc. The percentage of "ores" determines the order.

Order 1. 0 to 5 per cent "ores."
Order 2. 5 (inclusive) to 50 per cent "ores."
Order 3. 50 (inclusive) to 95 per cent "ores."
Order 4. 95 (inclusive) to 100 per cent "ores."

3. Determine the family. In Classes 1, 2, and 3, first recalculate the quarfeloids to 100. The amount of quartz (or feldspathoid) thus determined immediately locates a row of five horizontal pigeonholes, in one of which the rock belongs. Recalculate[1] Kf plus plagioclase to 100 and determine the proper point on the

[1] It is immaterial whether the orthoclase-plagioclase ratio is taken from the original values or from those reduced as quarfeloids to 100. The results are naturally the same.

Kf-Plag base line. This determines the vertical series of pigeonholes, and its intersection with the horizontal series gives the proper position for the family. (If plotted graphically, the family is directly determined by the position of the intersection of three lines, as shown in Example 1, below.) Only when the point falls very close to a division line is it necessary to compute the position accurately. The separation points for Kf-Plag are at 0–5–35–65–95–100.

In Class 4, Orders 1, 2, and 3, recalculate the olivine, pyroxene, and biotite plus amphibole to 100 (Fig. 5) and find the proper position graphically, or find the position analytically by taking the ratio of the mineral of one corner to each of the others; thus amphibole to olivine, amphibole to pyroxene, and olivine to pyroxene. The division points are 0–5–50–95–100.

In Class 4, Order 4, the writer groups all the ores in a single family, but classifies the various hematite, ilmenite, magnetite, etc., ores as subfamilies. If desired, they may be further separated. If accessory dark minerals, not used in the computation, are abundant, they determine subfamilies and may be mentioned in the rock name.

4. Subfamilies. In all classes subfamilies are based on 0–5–50–95–100 division points, after the manner shown in Figure 1.

A FEW POINTS TO BE OBSERVED

Any percentage value falling exactly on a line should be moved toward the opposite apex of the triangle except as indicated below. Thus a syenite with 5 per cent quartz is classified with granite, a rock with 95 per cent mafites belongs to Class 4, and one with 95 per cent quarfeloids to Class 2; $Ab_{95}An_5$ belongs to Order 2, and Ab_5An_{95} to Order 4. If the divisions fall on the 50-50 line of quartz they are moved upward, or on the 50-50 line of foids downward, toward the apices; that is, they are placed in Families 1 to 5 or 26 to 30. Rocks falling on the 50-50 light-dark line are classed with the dark, while along the plagioclase line $Ab_{50}An_{50}$ is classed with basic plagioclase. Rocks falling on the line separating the two triangles, namely, on the feldspar base line, usually should be classed on the quartz side, that is, on the normal side, but if

the rock has affinities with alkalic rocks it should be placed on the foid side.

In Class 4 the medial lines pass through the center of gravity of the triangle, consequently rocks falling on these lines are arbitrarily moved into the families shown by the small arrows in Figure 5.

For classificatory purposes, it is seldom necessary to make exact determinations of the mineral percentages. Unless the proportions are such that the rock falls near a division line, a simple inspection will answer. Thus it is usually possible to determine very quickly whether the dark constituents are less than 5 per cent, between 5 and 50 per cent, etc.; whether the quartz forms more or less than 5 per cent of the light constituents, and whether the orthoclase forms more than 95 per cent, between 95 and 65, between 65 and 35, between 35 and 5, or less than 5 per cent of the total feldspar. Of course, if the rocks are to be plotted as points in the triangle, more careful determinations are necessary.

EXAMPLES

Example 1.—A granodiorite having the composition

Quartz	18.0		= 23.1	
Orthoclase	18.0		= 23.1	= 30.0
Andesine ($Ab_{70}An_{30}$)	42.0		= 53.8	= 70.0
Total quarfeloids		78.0	100.0	100.0
Biotite	12.8			
Hornblende	9.0			
Magnetite	.1			
Titanite	.1			
Total mafites		22.0		
		100.0		

Percentage quarfeloids = 78. The rock belongs to Class 2.

$Ab_{70}An_{30}$ falls between 95 and 50. The order, therefore, is 2.

The family may be rapidly determined graphically. Plot 23.1 Qu, 23.1 Or, and 53.8 Ca*Naf* by drawing a horizontal line 23.1 above the base of the triangle, and an inclined line, parallel to the Qu-Plag line, 23.1 from that line. The intersection of the

two in Family 9 determines the position of the rock. As a check, the point must also lie 53.8 from the Kf-Qu line.

To compute the family analytically: From the presence of 23.1 per cent quartz, the family must lie between numbers 6 and 10, since there is more than 5 per cent and less than 50 per cent quartz. Further, the ratio of Or to Ca*Na*f is 30 to 70, and since the orthoclase is between 5 and 35 per cent the family number is 9.

The rock number, therefore, is 229, that is, Class 2, Order 2, Family 9. (The number is to be read two two nine.)

Example 2.—A nephelite-monzonite with

Kf	21.5		= 39.0	
Oligoclase ($Ab_{92}An_8$)	33.5		= 61.0	
Total feldspar		55.0	100.0	
Neph	27.5			
Sodal	8.5			
Total feldspathoids		36.0		
Total quarfeloids		91.0		
Aeg.-aug	5.0			
Biot	2.5			
Access	1.5			
		9.0		

Quarfeloid ratio 91, Class 2.

$Ab_{92}An_8$, Order 2.

Foids to feldspars = 36:55 = 39.5:60.5. Between Families 21 and 25.

Kf to Ca*Na*f = 39.0:61.0. Family 23.

Rock number is 2223. (To be read two two twenty-three.)

Example 3.—A lherzolite with

Augite	45.0 }	= 66.4
Hypersthene	20.0 }	
Olivine	30.0	= 30.6
Hornblende	3.0	= 3.0
		100.0
Magnetite	2.0	
	100.0	

Since there are neither feldspars, feldspathoids, nor quartz, the rock must belong to Class 4.

The ratio of ferromagnesian minerals to ores is 98:2; therefore the order is 1.

The ratio of pyroxene to olivine is 65:30=68:32; therefore the rock lies along the line of Families 6, 10, and 11. The ratio of pyroxene to hornblende is 65:3=96:4; therefore it belongs to Family 1, 4, 11, or 12. Family 11 is the only one common to both computations, consequently the rock number is 4111. (To be read four one eleven.)

The rock may be plotted by drawing one line parallel to the base and 30.6 above it, and another parallel to the amphibole-olivine line and 66.4 from it. The intersection of the two lines locates the rock. As a check, the third line, parallel to the remaining side of the triangle and at a distance of 3.0 from it, should cross the other two at their intersection.

NAMES PROPOSED FOR VARIOUS FAMILIES

On the basis of the foregoing subdivisions, nearly a thousand modal analyses have been plotted and names have been given to many of the families, most of them derived from plutonic rocks falling at the center points. In some cases, as in the quartz-rich types, family names were taken from differentiation rocks. In the tabulation (pp. 12–15) there are many blank pigeonholes, owing to lack of good modal descriptions. There are undoubtedly many rocks in most of the families here left blank, especially in Classes 2 and 3, but the majority of published rock descriptions lack mineral percentages, making them unavailable for classification. The writer is at present engaged in measuring the components of a great number of thin sections, most of them of classic rocks or of rocks which have been chemically analyzed.

Blank spaces in the tables below do not necessarily mean that rocks are wanting in these pigeonholes but may indicate that none falls near the center point, although, on the other hand, a solitary rare rock may, in some cases, give its name to the family, even though it is not at the center.

A certain system is used for the prefixes. The terms "granite," "syenite," "monzonite," "diorite," etc., are defined, and the addition of a prefix to any one indicates a definite modification. Where no specific name is available, "leuco-" is used to indicate rocks of Class 1, "meso-" those of Class 2, and "mela-" those of Class 3. In most cases the prefix "meso-" is unnecessary, since normal rocks belong to Class 2, and these are written without the prefix, the class being understood. Thus there are leuco-granites, granites, and mela-granites, respectively, in Classes 1, 2, and 3. Furthermore, syenites, monzonites, granodiorites, diorites, and even gabbros normally contain more than 5 and less than 50 per cent of dark constituents, whereby the prefix "meso-" is unnecessary.

Analogous rocks in the four orders of each class similarly have distinctive prefixes where no other names are available. The rocks of Order 1 have albite as their plagioclase; therefore an albite-monzonite is a monzonite whose plagioclase is albite, and in Order 4 an anorthite-monzonite is one containing orthoclase and anorthite. An albite-diorite means a rock all of whose plagioclase is albite; an albite-granite, on the other hand, means a granite containing some albite in addition to orthoclase, since granite itself is defined as a rock consisting of quartz, a biopyribole, orthoclase, and less plagioclase. That is to say, the term "granite" in itself conveys the idea of an orthoclase rock with some plagioclase, the latter indicated, except in normal rocks, by the prefix. The plagioclase in Order 2 is oligoclase to andesine, and that of Order 3 labradorite to bytownites. Acid and basic cannot be used as prefixes for these orders, since albite and anorthite, the end members of the acid and basic plagioclases, are set apart as Orders 1 and 2. Lime-soda and soda-lime are so much alike that one must always stop to think which is which. The prefixes "sodi-" and "calci-" are here suggested. As in the names of normal classes, here also normal rocks drop the prefix; "sodi-," therefore, is seldom necessary. To the rocks of the hinge families, namely those which contain no plagioclase, "ortho-" is prefixed; the feldspar present is orthoclase, microcline, microperthite, or anorthoclase.

TABLE I

CLASS I. $\frac{\text{Quarfeloids}}{\text{Mafites}}$ between $\frac{100}{0}$ and $\frac{95}{5}$

Order 1 $Ab_{100}An_0$ to $Ab_{95}An_5$	Order 2 $Ab_{95}An_5$ to $Ab_{50}An_{50}$	Order 3 $Ab_{50}An_{50}$ to Ab_5An_{95}	Order 4 Ab_5An_{95} to Ab_0An_{100}
0 Silexite..............	(=110)	(=110)	(=110)
1 Orthotarantulite	(=111)	(=111)	(=111)
2 Tarantulite	Granite-greisen		
3	Adamellite-greisen		
4	Granodiorite-greisen		
5	Tonalite-greisen		
6 Orthoalaskite	(=116)	(=116)	(=116)
7 Alaskite	Leucogranite		
8 Leuco-albite-adamellite	Leucoadamellite		
9 Leuco-albite-granodiorite	Leucogranodiorite	Leucogranogabbro	
10 Leuco-albite-tonalite	Leucotonalite	Quartz-anorthosite	
11 Orthosite	(=1111)	(=1111)	(=1111)
12 Leuco-albite-syenite	Leucosyenite		
13 Leuco-albite-monzonite	Leucomonozonite		
14 Leuco-albite-monzodiorite	Leucomonzodiorite	Leucomonzogabbro	Leuco-anorthite-monzogabbro
15 Albitite	Leucodiorite	Anorthosite	Anorthitite
16	(=1116)	(=1116)	(=1116)
17			
18			
19			
20	Dungannonite		
21	(=1121)	(=1121)	(=1121)
22			
23			
24 Leucolitchfieldite			
25 Leucomariupolite			
26	(=1126)	(=1126)	(=1126)
27			
28			
29			
30	Craigmontite		
31	(=1131)	(=1131)	(=1131)

TABLE II

CLASS 2. $\frac{\text{Quarfeloids}}{\text{Mafites}}$ between $\frac{95}{5}$ and $\frac{50}{50}$

Order 1 $Ab_{100}An_0$ to $Ab_{95}An_5$	Order 2 $Ab_{95}An_5$ to $Ab_{50}An_{50}$	Order 3 $Ab_{50}An_{50}$ to Ab_5An_{95}	Order 4 Ab_5An_{95} to Ab_0An_{100}
0 Meso-silexite	(=210)	(=210)	=(210)
1 Moyite	(=211)	(=211)	(=211)
2	Quartz-granite		
3	Quartz-adamellite		
4	Quartz-granodiorite		
5 Rockallite	Quartz-tonalite		
6 Orthogranite	(=216)	(=216)	(=216)
7 Albite-granite	Granite	Calcigranite	Anorthite-granite
8 Albite-adamellite	Adamellite	Calciadamellite	Anorthite-adamellite
9 Albite-granodiorite	Granodiorite	Granogabbro	Anorthite-granogabbro
10 Albite-tonalite	Tonalite	Quartz-gabbro	Quartz-anorthite-gabbro
11 Orthosyenite	(=2111)	(=2111)	(=2111)
12 Albite-syenite	Syenite	Calcisyenite	Anorthite-syenite
13 Albite-monzonite	Monzonite	Calcimonzonite	Anorthite-monzonite
14 Albite-monzodiorite	Monzodiorite	Monzogabbro	Anorthite-monzogabbro
15 Albite-diorite	Diorite	Gabbro, Norite	Anorthite-gabbro
16 Pulaskite	(=2116)	(=2116)	(=2116)
17	Nephelite-bearing syenite		
18	Nephelite-bearing monzonite		
19	Nephelite-bearing monzodiorite		
20	Nephelite-bearing diorite		
21 Ortho-nephelite-syenite	(=2121)	(=2121)	(=2121)
22 Albite-nephelite-syenite	Nephelite-syenite		
23 Albite-nephelite-monzonite	Nephelite-monzonite	Kulaite	
24 Litchfieldite	Nephelite-monzodiorite	Nephelite-monzogabbro	
25 Mariupolite	Nephelite-diorite	Nephelite-gabbro	
26 Naujaite	(=2126)	(=2126)	(=2126)
27 Beloeilite		Heronite	
28			
29			
30 Toryhillite		Lugarite	
31 Urtite, Fergusite, Uncompahgrite	(=2131)	(=2131)	(=2131)

TABLE III

CLASS 3. $\frac{\text{Quarfeloids}}{\text{Mafites}}$ between $\frac{50}{50}$ and $\frac{5}{95}$

Order 1 $Ab_{100}An_0$ to $Ab_{95}An_5$	Order 2 $Ab_{95}An_5$ to $Ab_{50}An_{50}$	Order 3 $Ab_{50}An_{50}$ to Ab_5An_{95}	Order 4 Ab_5An_{95} to Ab_0An_{100}
0	(=310)	(=310)	(=310)
1	(=311)	(=311)	(=311)
2			
3			
4			
5			
6 Mela-orthogranite	(=316)	(=316)	(=316)
7 Mela-albite-granite	Melagranite	Mela-calcigranite	
8 Mela-albite-adamellite	Mela-adamellite		
9 Mela-albite-granodiorite	Melagranodiorite	Melagranogabbro	
10 Mela-albite-tonalite	Melatonalite	Mela-quartz-gabbro	
11 Mela-orthosyenite	(=3111)	(=3111)	(=3111)
12 Mela-albite-syenite	Melasyenite		
13 Mela-albite-monzonite	Melamonzonite		
14 Mela-albite-monzodiorite	Melamonzodiorite	Melamonzogabbro	Ricolettaite
15 Mela-albite-diorite	Meladiorite	Melagabbro	Yamaskite
16 Orthoshonkinite	(=3116)	(=3116)	(=3116)
17 Shonkinite	Oligoclase-(andesine-) shonkinite	Labradorite-(bytownite-)shonkinite	
18			
19			
20			
21 Nephelite-shonkinite	(=3121)	(=3121)	(=3121)
22			
23			
24 Melalitchfieldite		Mela-nephelite-monzogabbro	
25 Melamariupolite		Theralite	
26	(=3126)	(=3126)	(=3126)
27			
28			
29			
30			
31 Bekinkinite, Missourite, Farrisite	(=3131)	(=3131)	(=3131)

TABLE IV

CLASS 4. $\frac{\text{Quarfeloids}}{\text{Mafites}}$ between $\frac{5}{95}$ and $\frac{0}{100}$

Order 1 "Ores" less than 5 Per Cent	Order 2 "Ores" between 5 and 50 Per Cent	Order 3 "Ores" between 50 and 95 Per Cent	Order 4 "Ores" more than 95 Per Cent
1 Dunite	Chromite-dunite Magnetite-dunite	Olivine-chromitite Olivine-magnetite	Chromitite Magnetite
2 Mica-peridotite, amphibole-peridotite, hornblende-picrite, cortlandtite.			
3 Valbellite, hornblende-diallage-peridotite, etc.			
4 Lherzolite, diallage-peridotite, wehrlite, harzburgite, saxonite.			
5 Included with Family 2 at present.			
6 Included with Family 3 at present.			
7 Cromaltite, hornblende-hypersthenite, etc.			
8 Amphibolites, hornblendites.			
9 Included with Family 7 at present.			
10 Included with Family 3 at present.			
11 Included with Family 4 at present.			
12 Diallagite, hypersthenite, websterite, ilmenite-enstatitite, etc.			

CLASS 1, ORDER 1

(110) Silexite MILLER. The term silexite was proposed by Miller[1] for pure igneous quartz rocks. Such rocks, frequently described under the names igneous quartz, quartz dikes, quartz veins, etc., represent the end members of pegmatitic intrusions. Greisen, an old Saxon miner's term, cannot be used for the family name, since it should properly be restricted to tin-bearing leucogranites. Furthermore, according to some authors, it is an altered rock, feldspar having been changed to quartz. Beresite ROSE[2] likewise cannot be used; it was shown by Helmhacker[3] to be an altered quartz-porphyry.

Besides pure quartz there are a number of other rocks falling in this family, namely such as are free from feldspars and mafites, and

[1] William J. Miller, "Silexite, a New Rock Name," *Science*, XLIX (1919), 149; also "Pegmatite, Silexite, and Aplite of Northern New York," *Jour. Geol.*, XXVII (1919), 28–54, in particular p. 30.

[2] Gustav Rose, *Mineralogisch-geognostische Reise nach dem Ural, dem Altai und dem Kaspischen Meere* (Berlin, 1837), I, 186.

[3] R. Helmhacker, "Der Goldbergbau der Umgebung von Berëzovsk am östlichen Abhange des Urals," *Berg- und Hüttenmännische Zeitung*, LI (1892), 83–84.

consist only of quartz and an auxiliary mineral, such as mica, tourmaline, topaz, etc. Among these are:

Esmeraldite Spurr. The terms greisen and beresite have been used more or less loosely for quartz-muscovite rocks, although, as mentioned above, they have other meanings. Spurr[1] definitely applied the term esmeraldite to rocks from the southern Klondike district, Esmeralda County, Nevada, which consist only of quartz and muscovite.

Syn.: Greisen (in part), Glimmer-greisen Jokély.[2]

Tourmalite.[3] This term is here suggested for rocks consisting only of tourmaline and quartz, to which the name hydrotourmalite was given by Daubrée.[4] Other synonyms are Schörlquarzit, Schörlfels, Schörlschiefer, Turmalinschiefer, Turmalinfels, schorl-rock, Carvoeira,[5] etc.

Topazite. Topazite is here suggested for rocks containing only quartz and topaz.

Syn.: Topasfels Werner,[6] Topazogène Charpentier,[7] topaz-rock.

(111) **Orthotarantulite.** The prefix "ortho-" is used here and in all of the hinge families to indicate feldspathic rocks which contain less than 5 per cent plagioclase. They include, therefore, orthoclase, microcline, microperthite, and anorthoclase rocks. See note under (112). Thus defined, orthotarantulite is a tarantulite with less than 5 per cent of its feldspar plagioclase.

[1] J. E. Spurr, "The Southern Klondike District, Esmeralda County, Nevada," *Econ. Geol.*, I (1906), 382.

[2] Johann Jokély, "Das Erzgebirge im Leitmeritzer Kreise in Böhmen," *Jahrb. d. k. k. geol. Reichsanst.*, IX (1858), 566.

[3] In the following pages proposed new names are in bold-face type. Where the prefix indicates a newly formed group it is shown thus, **ortho**granite.

[4] M. Daubrée, "Sur le gisement, la constitution et l'origine des amas de minerai d'étain," *Ann. d. Mines*, XX (1841), 84.

[5] W. L. v. Eschwege, *Beiträge z. Gebirgskunde Brasiliens* (1832), p. 178.

[6] A. G. Werner, *Kurze Klassification und Beschreibung der verschiedener Gebirgsarten* (Dresden, 1787), p. 15.

[7] J. de Charpentier, *Vom Schneckenstein, oder dem sächsischen Topasfelsen* (Prag, 1776).

Syn.: Alaskite-quartz SPURR (in part),[1] Feldspar-greisen JOKÉLY (in part).

(112) **Tarantulite.** Spurr[2] used the term alaskite-quartz for a transition rock between alaskite and igneous quartz which occurs in the Missouri mine, near Tarantula Spring, Nevada. As a simpler term the name tarantulite is here proposed for Family 2, which contains orthoclase and less albite.

Syn.: Alaskite-quartz SPURR (in part), Feldspar-greisen JOKÉLY (in part).

(116) **Ortho**alaskite. The term alaskite was given by Spurr[3] to leucocratic rocks which contain alkali feldspars (orthoclase, microcline, microperthite), with or without albite. Here they are divided into two groups. Those without albite are included under the name orthoalaskite (see note under (111)), while those with albite are normal alaskites of Family 7 (117).

Runite PINKERTON.[4] Syn.: Pegmatite HAÜY,[5] Schriftgranit, Hebräischerstein, graphic-granite, etc.

Orthotordrillite. The extrusive equivalent of orthoalaskite is orthotordrillite. The name tordrillite was given by Spurr[6] to the extrusive equivalent of alaskite. In the present classification only the tordrillites with no plagioclase are included in this family.

(117) Alaskite SPURR. See under orthoalaskite (116).

Tordrillite SPURR. See under orthotordrillite (116) above.

Syn.: Rhyalaskite.[7]

[1] J. E. Spurr, "Ore Deposits of the Silver Peak Quadrangle, Nevada," *U.S. Geol. Surv., Prof. Paper 55* (1906), p. 61.

[2] *Ibid.*

[3] J. E. Spurr, "Classification of Igneous Rocks According to Composition," *Amer. Geol.*, XXV (1900), 229–30.

[4] J. Pinkerton, *Petrology* (London, 1811), II, 85.

[5] Ascribed to Haüy by Brongniart, "Essai d'une classification minéralogique des roches mélangées," *Jour. d. Mines*, XXXIV (1813), 32.

[6] J. E. Spurr, "Classification of Igneous Rocks According to Composition," *Amer. Geol.*, XXV (1900), 230; also "Reconnaissance in Southwestern Alaska in 1898," *U.S. Geol. Surv., Ann. Rept.*, XX, Part VII (1900), p. 189.

[7] J. H. Farrell, *Field Geology* (New York, 1912), p. 160, Table II.

(118) **Leuco-albite**-adamellite. No confusion can result here from the use of the word albite as a prefix (see p. 48, above). It cannot be thought to mean that the albite replaces (proxies) the potash feldspar, since the term adamellite conveys the quartz-monzonitic idea, but it clearly shows that the plagioclase present is albite. For the use of the term adamellite for quartz-monzonite see note under (228).

Leuco-albite-dellenite. The extrusive equivalent of the preceding.

(119) **Leuco-albite**-granodiorite. See note under (118).

(1110) **Leuco-albite**-tonalite. See note under (118). For the use of tonalite for quartz-diorite see (2210).

(1111) Orthosite TURNER. These rocks are leuco-potash-syenites or leuco-orthosyenites. For those composed entirely of orthoclase, Turner[1] proposed the term orthosite. Pure anorthoclase or sanidine rocks belong here also. The former might properly be called anorthosites. This term, however, is now so firmly attached to plagioclase rocks without mafites that no change is possible. See note under anorthosite (1315).

Sanidinite TSCHERMAK.[2]

Microclinite LOEWINSON-LESSING.[3]

Anorthoclasite LOEWINSON-LESSING.[4]

(1112) **Leuco-albite**-syenite. A temporary term for leucocratic syenites, consisting essentially of orthoclase with some albite. See note under (217).

(1115) Albitite TURNER. Turner's[5] term for rocks which consist essentially of albite.

(1124) **Leucolitchfieldite**. See note under (2124). This term is preferable to the longer term leuco-albite-nephelite-monzodiorite.

[1] H. W. Turner, "The Nomenclature of Feldspathic Granolites," *Jour. Geol.*, VIII (1900), 106–10.

[2] Gustav Tschermak, "Verhandlungen der k. k. geol. Reichs. Sitzung am 6 März, 1866," *Jahrb. d. k. k. geol. Reichsanst.*, XVI (1866), 34.

[3] F. Loewinson-Lessing, "Kritische Beiträge zur Systematik der Eruptivgesteine," *Tscherm. Min. Petr. Mitth.*, XX (1901), 114.

[4] *Loc. cit.*

[5] H. W. Turner, "The Nomenclature of Feldspathic Granolites," *Jour. Geol.*, VIII (1900), 111.

(1125) Leucomariupolite. See note under (2125). It is a leuco-albite-nephelite-diorite.

(1131) Here belong rocks consisting of one or more feldspathoids, without feldspars or dark constituents. The type rock is pure nephelite. For the corresponding extrusives Loewinson-Lessing[1] proposed noseanite, nephelinolith, and amphigenite. Noseanite, however, was previously used by Bořický[2] for an amphibole-(plus 50 per cent) nephelite-(20–40 per cent) noselite rock with small amounts of magnetite and olivine, while amphigenite was used by Cordier[3] for rocks now called leucite-tephrites.

Sodalitsten Steenstrup[4] probably belongs to this family.

CLASS 1, ORDER 2

(120) These rocks are included under Order 1, since the variations produced by small amounts of different plagioclases are unessential.

(121) Included under Order 1.

(122) Granite-greisen Jokély. Syn.: Feldspathgreisen Jokély. Jokély[5] applied the term Granit- or Feldspathgreisen to rocks consisting essentially of quartz and feldspar with some muscovite. The feldspar was determined megascopically only and was spoken of as "allem Anschein nach durchgänglich Orthoklas." If ordinary granites are divided into orthogranites and normal granites, so also should the granite-greisens be divided, and there would be orthogranite-greisens (121) and granite-greisens (122). But (121) is the hinge family and is the same as (111); consequently the former name need not be considered, and the term granite-greisen can be applied to the quartz-feldspar rock of Family 2. The presence or absence of muscovite will not change the classification,

[1] F. Loewinson-Lessing, "Kritische Beiträge zur Systematik der Eruptivgesteine, IV," *Tscherm. Min. Petr. Mitth.*, XX (1901), 114.

[2] Emanuel Bořický, "Petrographische Studien an den Basaltgesteinen Böhmens," *Arch. f. d. naturw. Landesdurchf. v. Böhmen*, Band II, Abt. ii, Th. ii, pp. 41, 78–79.

[3] Cordier and d'Orbigny, *Description des roches* (Paris, 1868), pp. 114–15.

[4] N. V. Ussing, "Mineralogisk-petrografiske Undersögelser af Grönlandske Nefelinsyeniter og beslaegtede Bjaergarten, 1894," *Meddel. om Grönl.*, XIV (1898), 128.

[5] Johann Jokély, "Das Erzgebirge im Leitmeritzer Kreise in Böhmen," *Jahrb. d. k. k. geol. Reichsanst.*, IX (1858), 567.

though when it is present the rock may be classed as a subfamily, comparable to one in the normal granite family, namely as Muscovite-granite-greisen.

(123) **Adamellite-greisen.** The rock for which the term adamellite-greisen is here proposed is related to the quartz-monzonites (adamellites) as granite-greisen is to normal granite. For the use of the term adamellite for quartz-monzonite see note under (228).

(124) **Granodiorite-greisen.** See note under (123).

(125) **Tonalite-greisen.** See note under (123).

(127) **Leuco**granite differs from normal granite (227) in the practical absence of mafic minerals. It therefore consists of quartz, orthoclase, and a less amount of oligoclase or andesine.

Leucorhyolite. The extrusive equivalent of the preceding.

(128) **Leuco**adamellite. See note under (127).

Leucodellenite. The extrusive equivalent of the preceding.

(129) **Leuco**granodiorite. See note under (127).

Leucorhyodacite. The extrusive equivalent of preceding. See note under rhyodacite (229).

(1210) **Leuco**tonalite. See note under (127) for the relationship between this rock and normal tonalite. For the use of tonalite for quartz-diorite see (2210). According to the kind of feldspar present, the leucotonalites are divided into quartz-oligosites TURNER (quartz-oligoclasites), and quartz-andesinites TURNER. See note under (1215).

Quartz-oligosite TURNER.

Quartz-andesinite TURNER.

Leucodacite. The extrusive equivalent of leucotonalite.

(1212) **Leuco**syenite. See note under (127).

Leucotrachyte. The extrusive equivalent of preceding.

(1213) **Leuco**monzonite. See note under (127).

Leucolatite. The extrusive equivalent of preceding.

(1214) **Leucomonzodiorite.** In the former paper the writer[1] suggested the term syenodiorite, from analogy with granodiorite,

[1] Albert Johannsen, "Suggestions for a Quantitative Mineralogical Classification of Igneous Rocks," *Jour. Geol.*, XXV (1917), 89.

for quartz-free plagioclase rocks with some orthoclase. Under (229) he shows the objection to the term granodiorite, an objection which also applies to the word syenodiorite. The latter term, consequently, is here withdrawn, and monzodiorite is substituted as better indicative of a rock intermediate between monzonite and diorite. Leucomonzodiorite is the name of the corresponding rock in Class 1.

Leucoandelatite. See note under (2214). The extrusive equivalent of preceding. Leucotrachyandesite would be the extrusive name by analogy with granodiorite, but trachyandesite has been used in the sense of latite as well as for an intermediate rock of the foyaite series[1] and comparable to trachydolerite of the gabbro series.

(1215) **Leuco**diorite. According to the kind of plagioclase present, the leucodiorites are divided into oligosites Turner[2] (oligoclasites) and andesinites Turner.[3]

Oligosite Turner.

Andesinite Turner.

Leucoandesite. The extrusive equivalent of leucodiorite.

(1220) Dungannonite Adams and Barlow. A leucocratic nephelite-bearing diorite with considerable corundum (13.24 per cent) from Dungannon, Ontario, was described and named dungannonite by Adams and Barlow.[4] It is not typical of the family on account of the presence of corundum, but the name is here used since this rock is the only representative of the family yet located in the literature.

(1230) Craigmontite Adams and Barlow. The name craigmontite was given by Adams and Barlow[5] to a nephelite-oligoclase-muscovite rock from Craigmont, Ontario. While the mode given

[1] H. Rosenbusch, *Mikroskopische Physiographie der massigen Gesteine* (4th ed.; Stuttgart, 1908), p. 1036.

[2] H. W. Turner, "The Nomenclature of Feldspathic Granolites," *Jour. Geol.*, VIII (1900), 111.

[3] *Ibid.*

[4] Frank D. Adams and Alfred E. Barlow, "Geology of the Haliburton and Bancroft Areas, Province of Ontario," *Geol. Surv. Canada, Mem. 6* (Ottawa, 1910), p. 322.

[5] *Ibid.*, p. 313.

in the report of the Canadian Geological Survey is calculated from the analysis, the actual mineral composition is probably also represented by it. The craigmontite type contains muscovite, but the name may be applied, with a proper prefix, to any oligoclase-nephelite rock of Family 30, for example aegirite-craigmontite, etc.

CLASS 1, ORDER 3

(139) **Leucogranogabbro.** While adam-gabbro would be more correct than granogabbro for the rocks of this family, the term is objectionable in sound, and, furthermore, since granodiorite is so firmly established that it must be retained, granogabbro as an analogous term should also be retained. See note under granodiorite (229).

Leucorhyobasalt. For the same reason that rhyodacite is retained rhyobasalt is used. See note under (229). Strictly speaking the term should be leuco-rhyo-quartz-basalt, but the prefix "rhyo-" may be considered as indicative of the presence of quartz.

(1310) Quartz-anorthosite. See note under (1315).

Leuco-quartz-basalt. The extrusive of the above.

(1314) **Leucomonzogabbro.** The objection to syenodiorite, mentioned under (1214), applies also to syenogabbro, which was previously proposed by the writer.[1] That term is now withdrawn and monzogabbro is substituted. See note under (2314).

(1315) Anorthosite Hunt. The term anorthosite was proposed by T. Sterry Hunt[2] for rocks composed chiefly of plagioclase (labradorite in most Canadian occurrences). The name is derived[3] from *anorthose,* originally used by Delesse for triclinic feldspars, although now used for anorthoclase. Anorthosite, consequently, properly should not be applied to plagioclase rocks. It is in such general use, however, that it must either be dropped entirely or else used in the sense of Hunt. Turner[4] would apply the term

[1] Albert Johannsen, "Suggestions for a Quantitative Mineralogical Classification of Igneous Rocks," *Jour. Geol.,* XXV (1917), 89.

[2] T. Sterry Hunt, *Geology of Canada* (Montreal, 1863), p. 22.

[3] Frank D. Adams, "Über das Norian oder Ober-Laurentian von Canada," *Neues Jahrb., B.B.,* VIII (1893), 423.

[4] H. W. Turner, "The Nomenclature of Feldspathic Granolites," *Jour. Geol.,* VIII (1900), 106–11.

to anorthoclase rocks without mafic minerals, and would divide the basic plagioclase rocks, now called anorthosites, into labradites and anorthitites, according to the kind of plagioclase present, presumably dividing the bytownite rocks between them. Since most anorthosites are labradorite rocks, the term may well be confined to the labradorite-bytownite rocks of Class 1, Order 3, leaving the anorthite rock, anorthitite, in a class by itself (1415).

Labradite TURNER.

Bytownitite.

Leucobasalt. The extrusive equivalent of anorthosite.

CLASS 1, ORDER 4

(1414) **Leuco-anorthite-monzogabbro.** A simpler name should be used here when a rock near the center point is described.

(1415) Anorthitite TURNER.[1] See note under (1315).

[1] *Ibid.*

[*To be continued*]

THE PRE-MOENKOPI (PRE-PERMIAN?) UNCONFORMITY OF THE COLORADO PLATEAU

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There is a growing appreciation of the importance of the unconformity below the "Red Bed" series of the Colorado Plateau Province, as witnessed by the recent paper of Lee[1] on the subject. During a reconnaissance in southeastern Utah, northeastern Arizona, and northwestern New Mexico, the writer had an opportunity to gather some additional data on the extent and possible magnitude of the stratigraphic break, and these facts are herewith presented.

The first part of the paper deals with the local evidences of the unconformity at several points, particularly at Mule Twist Canyon, Utah; at Fruita, Utah; in Quartzite Canyon, near Fort Defiance, Arizona; at Ramah, New Mexico, on the Zuni Uplift; and near Tolchico, Arizona, on the Little Colorado River. The location of all these points is indicated on the accompanying sketch map (Fig. 1).

The second part of the paper begins with a summary of the known areal extent of the unconformity, and this is followed by a discussion of the magnitude of the stratigraphic break.

Since the formation names are largely local and probably unfamiliar to most readers, the following partial columnar section is given.

Jurassic,	La Plata sandstone
Triassic,	Dolores (Chinle) formation Shinarump conglomerate
Permian (?),	DeChelly sandstone (local) Moenkopi red beds

[1] W. T. Lee, "General Stratigraphic Break between Pennsylvanian and Permian in Western America," *Bull. Geol. Soc. Am.*, Vol. XXVIII (1917), pp. 169–70.

Carboniferous,	Kaibab limestone	Upper Aubrey group, Pennsylvanian
	Coconino sandstone	
	Supai formation	
	Redwall limestone, Pennslvanian and Mississippian	

DETAILED OCCURRENCES OF THE UNCONFORMITY

Mule Twist Canyon.—The first locality at which the unconformity was noted is about four miles northwest of Mule Twist

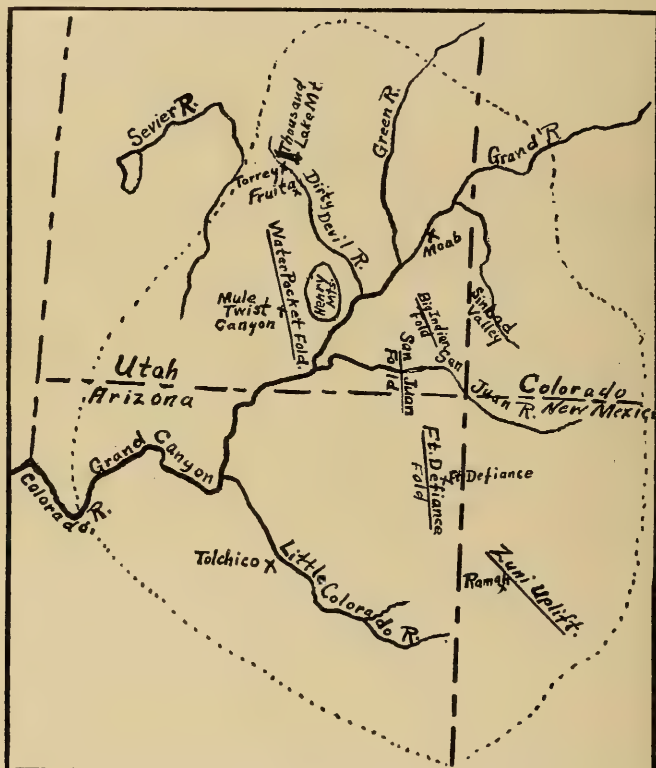

FIG. 1.—The Colorado Plateau

Canyon, a well-known pass through the La Plata "reef" or "ledge," a prominent escarpment on the east flank of the Water Pocket Flexure, west of Henry Mountains, Utah (Fig. 1). At this point the unconformity is distinctly indicated by basal conglomerates, by the uneven surface on which the Moenkopi rests, and by the

variable thickness of the Moenkopi itself. The following detailed section was measured in this vicinity:

SECTION NEAR MULE TWIST CANYON

(4)	100 feet	red and yellowish-gray sandy shale and some sandstone
(3)	60 feet	well-bedded gray fossiliferous limestone
(2)	40 feet	regularly bedded calcareous sandstone
(1)	75 feet	massive cross-bedded gray sandstone, base not exposed

The gray standstone and limestone are undoubtedly the Aubrey group of the Carboniferous mentioned by Gilbert[1] in the Henry

FIG. 2.—Cross-bedded Coconino(?) sandstone near Mule Twist Canyon, Water Pocket Flexure, near Henry Mountains, Utah.

Mountains. The limestones and upper bedded sandstones (members 2 and 3) were sparingly fossiliferous, and several species were collected, but the collection was unfortunately lost by the burning of an office building in which the writer was temporarily quartered. The fauna was totally unfamiliar to the writer, and consisted of very small crinoid stems, several pelecypods, and one or two small brachiopods. They did not resemble at all the faunas so abundant in the Goodridge formation of the San Juan Oil Field, a formation

[1] G. K. Gilbert, *The Geology of the Henry Mountains*, 1880.

provisionally correlated with the Redwall limestone. The cross-bedded sandstone (member 1) resembles very closely the Coconino. (Cf. Figs. 2 and 3 of this paper with Plates XXIX A and B, *U.S. Geol. Surv., Bull. 613*, which illustrate the Coconino in Walnut Canyon, Arizona.) The red and yellowish-gray sandy shales of number four rest on the slightly eroded surface of the limestone (member 3) with a very sparing development of conglomerate at the contact. The shales are gray at the base, but grade upward

FIG. 3.—Cross-bedding in Coconino(?) sandstone, same locality as Fig. 2. Photo by Zoller.

irregularly into the typical red sandy shales of the Moenkopi, which are in turn overlain, again with unconformity (Fig. 4), by the coarse sandstone and conglomerate of the Shinarump (restricted), and this is followed by typical Dolores and La Plata.

At this point the unconformity is not very pronounced. About two miles northwest, however, near the south end of Wagon Box Mesa, a large mesa capped with Shinarump, the deeper valleys show red shale grading down through gray sandy shale into coarse sandy conglomerate. The conglomerate consists of pebbles of chert and limestone in a sand matrix, and rests directly on gray, cross-bedded sandstone. At this point the limestone seems to have been removed by the pre-Moenkopi erosion. Here, at the south end of the Wagon

Box Mesa, the Moenkopi is about four hundred to five hundred feet thick. Two miles north of the north end of the mesa, perhaps four miles from the last point described, occur some smaller mesas, also capped with Shinarump. Here the Moenkopi is not over two hundred feet thick. The change may in part be due to the post-Moenkopi, pre-Shinarump erosion, but is more probably owing to the uneven surface of the Aubrey beds, on which the Moenkopi was laid down. This seems the more probable, since

FIG. 4.—Unconformity of Shinarump conglomerate on Moenkopi beds, west of Wagon Box Mesa, Water Pocket Flexure, Utah.

at this point the Moenkopi is again noted to rest on the limestone member. In this vicinity the upper ledge of the limestone is itself distinctly conglomeratic.

The foregoing facts indicate a decided erosion of the Aubrey before the Moenkopi was deposited, an erosion amounting in places to probably two hundred feet or more, with the complete removal, at certain points, of the limestone beds, allowing the shales to rest directly on the cross-bedded sandstone member.

Fruita.—At Fruita, about forty miles northwest of the Mule Twist locality, the canyon of the Dirty Devil (Fremont) River cuts deeply into gray limestones and sandstones below the "Red

Beds." A rather detailed section was measured along this canyon, and the section is given below.

SECTION IN DIRTY DEVIL CANYON, NEAR FRUITA

26	50+feet	red shale, Moenkopi, slightly irregular contact, with a few pebbles
25	50 feet	limestone in massive ledge
24	55 feet	red shale
23	10 feet	covered slope
22	60 feet	limestone, chalky at base, sandy in middle, cherty at top
21	12 feet	covered slope
20	40 feet	white chalky limestone, with chert concretions
19	20 feet	covered
18	20 feet	gray limestone, weathers with a powdery surface
17	20 feet	covered
16	2 feet	chert
15	170 feet	non-bedded sandstone, very coarse at base, finer above
14	30 feet	sandy limestone, with quartzite ledges
13	13 feet	yellowish, very cross-bedded sandstone
12	4 feet	sandy gray limestone
11	12 feet	cross-bedded coarse white sandstone
10	15 feet	sandy gray limestone
9	10 feet	coarse gray sandstone
8	18 feet	thin-bedded argillaceous limestone
7	122 feet	cross-bedded coarse white sandstone
6	125 feet	cross-bedded white sandstone with some thin shale lenses
5	2 feet	thin-bedded shaly sandstone
4	45 feet	cross-bedded white sandstone
3	2–6 inches	greenish-gray shale
2	40 feet	massive cross-bedded coarse white sandstone
1	12 feet	covered slope above river
	957 feet, all of which, except number 26, are Aubrey.	

There is nothing in the section above that can be correlated with any great certainty with the individual beds in the vicinity of Mule Twist Canyon. Member number 15 may possibly represent the sandstones of the Mule Twist region, though this is uncertain. If it does, there are many more beds between it and the Moenkopi here than in the former section. The unconformity

itself is not particularly well marked in the vicinity of Fruita, but the entirely different character of the beds on which the Moenkopi rests here and near Mule Twist constitutes a difference which perhaps might result from lateral variation, but which more probably indicates a different horizon as the base on which the Moenkopi beds were deposited. No fossils were seen in the Fruita section.

About ten miles northwest of Fruita, and perhaps three miles southeast of Torrey, the following section was measured across the contact:

SECTION NEAR TORREY, UTAH

16	... feet	red sandy shale
15	15 feet	gray shale
14	75 feet	red sandy shale
13	20 feet	gray to brown, thin-bedded sandstone
12	35 feet	red sandy shale, ripple-marked
11	15 feet	covered slope
10	14 feet	thin-bedded sandy gray limestone, upper contact concealed
9	2 feet	very crystalline, pitted gray limestone
8	16 feet	thin-bedded argillaceous limestone
7	5 feet	covered
6	15 feet	crystalline gray pitted limestone
5	3 feet	argillaceous white sandstone
4	3 feet	gray crystalline limestone
3	3 feet	fine-grained argillaceous white sandstone
2	52 feet	massive gray limestone
1	42+feet	red shale with gypsum veins, base not exposed

The boundary of the Pennsylvanian and the Moenkopi is here believed to occur between members 10 and 11. The red shale (number 1) of this section, below the fifty-two-foot ledge of gray limestone, is believed to correspond to the fifty-five feet of red shale (number 24) in the Fruita section, also below fifty feet of massive limestone. Beds 3 to 10 of the Torrey section seem to have been eroded off at Fruita.

Ramah.—On the west flank of the Zuni Uplift, about six miles east of Ramah, New Mexico, along a sharp canyon, followed by the main wagon road, the situation is as follows: about fifty feet of red sandy shales and sandstones rest with very uneven contact

on gray massive limestones, of which perhaps fifty to one hundred feet are exposed. No fossils were noted, but it is confidently believed that the gray limestone is Aubrey and the red sandy shales and sandstones Moenkopi. The marked uneven character of the contact leaves no room for doubt as to the unconformable relation between them.

Above the Moenkopi is a thin conglomeratic sandstone taken to be the Shinarump, since above it rest characteristic ashy gray and purple shales highly suggestive of the typical Chinle (Dolores),

FIG. 5.—Nearly flat-lying Moenkopi unconformable on folded pre-Cambrian, Quartzite Canyon, near Fort Defiance, Arizona.

so widely exposed in the De Chelly (Fort Defiance) Uplift.[1] The exceptional thinness of the Moenkopi here (50 to 100 feet) may be due in part to post-Aubrey and pre-Moenkopi erosion, in part to post-Moenkopi and pre-Shinarump erosion, and possibly in part to lack of deposition. No information was secured which would enable one to decide which of these might be the most important factor.

Fort Defiance.—In Quartzite Canyon, near Fort Defiance, Arizona, the Moenkopi rests directly on steeply dipping, much jointed, vitreous quartzite (Figs. 5 and 6). This relation has

[1] H. E. Gregory, "Geology of the Navajo Country," *U.S. Geol. Surv., Prof. Paper 93*, 1917.

already been described by Gregory,[1] who says of it: "If strata of Pennsylvanian age once covered the quartzite the pre-Moenkopi erosion interval, elsewhere poorly marked, becomes here a stratigraphic feature of great significance. In my opinion the quartzite is a monadnock of a pre-Cambrian erosion surface—an elevated mass which outlived its contemporaries through Cambrian, Silurian,

FIG. 6.—Same unconformity as in Fig. 5

Devonian, and early Carboniferous time, only to be itself buried by the streams of Permian time." It would appear from this statement that Gregory does not incline to believe that the quartzite-Moenkopi unconformity is related to the Pennsylvanian-Permian erosion interval, but represents earlier unconformity with overlap. Here also it is not possible to determine the facts.

[1] H. E. Gregory, *loc. cit.*

Tolchico.—Gregory[1] sums up briefly evidence presented by several writers, pointing to unconformity at the base of the Moenkopi, which seems to be especially marked along the Little Colorado. The writer has seen the area described by Gregory near Tolchico, and while there is clear evidence both of pre-Moenkopi erosion channels and basal Moenkopi conglomerate, neither the eroded contact nor the conglomerate are as well developed here as near Mule Twist Canyon, west of Henry Mountains, unless the conditions described below are related to pre-Moenkopi erosion.

At a sharp bend in the Little Colorado River, perhaps two or three miles northwest of Tolchico, a deep sharp canyon is cut in the Kaibab limestone, and a sharply cut tributary canyon enters at the bend, from the southwest. Perhaps a quarter of a mile up the tributary canyon from its mouth occur conditions of peculiar interest. Within the canyon, which here cuts between seventy-five and one hundred feet into the Kaibab, and resting against the Kaibab walls with distinct and coarse basal conglomerate, are very friable, intricately cross-bedded, rather coarse sandstones. In color they are dark red, deep brown, and in places almost black, in which respect they contrast strongly with the gray limestone walls of the canyon between which they lie, and also with the cream-colored, white, or gray drifts of dune sand which surround them, in turn, and partly bury them. Their age was not determined, since they appear to be absolutely unfossiliferous. At first the writer inclined to the idea that they were a phase of the basal Moenkopi, resting in an old pre-Permian channel, and while he still admits the possibility of this interpretation, it is also considered possible and perhaps probable that they are a wind-blown deposit of Tertiary or early Quaternary age, consisting largely of materials derived from the Moenkopi. That they rest in a channel cut at least one hundred feet into the Kaibab limestone, that they contain a coarse basal conglomerate of limestone bowlders, and that they are distinctly older than the present dune sands, admit of no question whatever. The general character and relations of these deposits can be studied more clearly from the illustrations given (Figs. 7 and 8).

[1] H. E. Gregory, *op. cit.*, p. 21.

AREAL EXTENT OF THE UNCONFORMITY

Many other workers who have studied the stratigraphy of this region have recognized the prevailing unconformity at the base of the Moenkopi, but in general it has heretofore been considered a minor break. The evidence goes to show that it is recognized over an area from the Little Colorado River in Arizona, east to the Zuni Uplift in New Mexico, and northwest to the Dirty Devil (Fremont) River in Utah.

FIG. 7.—Cross-bedded sandy shale (the two dark masses to the left of the center) resting in erosion channel in Kaibab limestone; dune sand in the foreground. On Little Colorado River, near Tolchico, Arizona.

In the San Juan Oil Field, which lies about midway between the Ramah and Fruita localities, the Moenkopi, according to Woodruff,[1] rests on the Goodridge (Redwall ?) limestone with "a sharp lithologic break," though he does not mention an actual erosion interval. Of the same place Gregory[2] says: "No undisputed evidence of unconformable relations between the Pennsylvanian and Permian (?) was obtained at this locality." He indicates, however, evidence of a probable break of importance in sedimentation. In view of

[1] E. G. Woodruff, "Geology of the San Juan Oil Field, Utah," *U.S. Geol. Surv., Bull. 471*, p. 87.

[2] H. E. Gregory, *op. cit.*, p. 21.

the unconformable relations both northwest and southeast, it is highly probable that the unconformity also exists along the San Juan.

STRATIGRAPHIC MAGNITUDE OF THE UNCONFORMITY

Stratigraphically, near Mule Twist Canyon, this unconformity represents at least two hundred feet of erosion. If the beds in the Mule Twist vicinity are actually different geological horizons

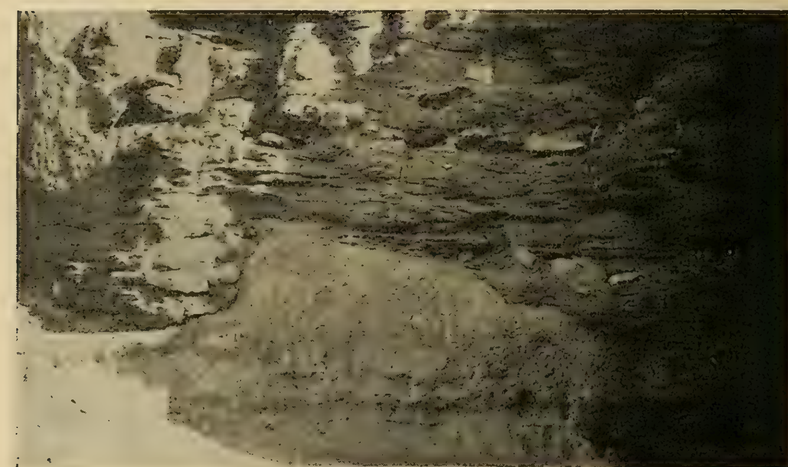

FIG. 8.—Detail of contact of sandy shale shown in Fig. 7, on Kaibab limestone. Note pebbles of limestone in the shale.

from those near Fruita, rather than different facies of the same horizon, a conclusion that seems highly probable, then the pre-Moenkopi erosion was even greater.

Let us examine now the significance of certain tentative correlations made by Girty and presented by Woodruff.[1] Regarding the age of the Goodridge limestone in the San Juan Field, Girty says:

I have already examined and reported upon a collection from the Honaker trail, where a good portion of Mr. Woodruff's material was obtained. This collection was made by Robert Forrester, of Salt Lake City, Utah. Mr. Forrester, who has done much work of a very accurate kind involving the Mesozoic

[1] E. G. Woodruff, *op. cit.*, pp. 75–104.

and late Paleozoic rocks of Utah, reports that his fossils came from what was called Lower Aubrey group in the reports of the Wheeler Survey, their Upper Aubrey being our Kaibab limestone. The lists of fossils given by Meek as representing the fauna of the upper Redwall limestone show the same general facies as Mr. Woodruff's collection. The typical Redwall we know to be of Pennsylvanian age in the upper part and Mississippian age in the lower part, so that the facts at hand seem to indicate that the strata involved in Mr. Woodruff's collection represent the upper part of the typical Redwall limestone. I do not regard it as certain, however, that the marked dissimilarity of the Kaibab fauna to anything which Mr. Woodruff found in his section may not be regional and that by gradual modification some of his faunas may not pass into the Kaibab fauna at the same geologic level.

If Girty is right in his tentative suggestion that the Goodridge is the equivalent of the Redwall, the pre-Moenkopi erosion interval at once assumes greatly added significance as a stratigraphic break of notable magnitude, for this would indicate the removal, or non-deposition, in the San Juan Field of the Supai sandstones and shales, the Coconino sandstone, and the Kaibab limestone, all of which occur above the Redwall in the Grand Canyon section, the combined thicknesses of which are not far from two thousand feet. This supposition is perhaps somewhat strengthened by the facts observed near Mule Twist, where the formations resemble closely the Kaibab and Coconino. The fossils collected by the writer, had they not been lost, might have settled this point. It is to be hoped that other collections may be secured soon from that locality. From this it would seem that the Moenkopi may be resting on Kaibab limestone near Tolchico and in the Grand Canyon, on Redwall limestone in the San Juan Oil Field, and again on Kaibab limestone and Coconino sandstone near Mule Twist Canyon.

The foregoing is a possibility which, the writer finds, has already been considered by Cross[1] in explaining the fact that the Pennsylvanian directly beneath the "Red Beds" at Moab carries a different and possibly older fauna than was found by Powell and Newberry below the Red Beds farther west on Colorado River. Cross says:

There may be a stratigraphic break, due to uplift and erosion, through which the Aubrey strata found by Powell and Newberry have been removed at Moab, in the Sinbad Valley, and to the mountain region to the east. This

[1] Whitman Cross, "Stratigraphic Results of a Reconnaissance in Western Colorado and Eastern Utah," *Jour. Geol.*, XV (1907), pp. 634–79.

implies that the Hermosa beds of Moab are present beneath the section examined by Powell and Newberry. Such a break must occur at the base of the Paleozoic "Red Beds," and no suggestion of such a hiatus has come from observations in Colorado; but it is to be remembered in this connection that in southern Utah and northern Arizona, Powell, Gilbert, Dutton, Walcott, and others have noted a persistent unconformity by erosion between the Aubrey and the succeeding strata now commonly referred to the Permian through Walcott's discovery of fossils in the Kanab Valley. All of the above-named geologists have observed a conglomerate more or less widely distributed at the base of the Permian series, composed in large part of pebbles derived from the Aubrey rocks, as shown by fossils contained in them. It is, of course, possible that the denudation at this horizon may have been much more extensive than the observations thus far reported would suggest.

The direction even of this change corresponds to the facts observed by the writer. According to the statement by Cross, the beds on which the Moenkopi rests are younger to the west, older to the east. Similarly the writer finds that in the San Juan Oil Field, about in the longitude of Moab, the Moenkopi rests on beds which are possibly as old as Redwall, while farther west, at Tolchico and at Mule Twist Canyon, the Moenkopi seems to be resting on younger beds, probably the Kaibab.

That the beds below the Moenkopi near Mule Twist Canyon were equivalent to the Kaibab and Coconino, and were not equivalent to the Goodridge, was the independent conclusion reached by the writer, even before he was aware of the foregoing statements by Girty and by Cross. In view of the uncertain condition of this correlation, it was felt that these few notes might add to the general knowledge regarding the extent and magnitude of this break.

PALEOZOIC DIASTROPHICS OF THE NORTHERN MEXICAN TABLELAND

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A little below the southern boundary of Colorado the Rocky Mountains, in a triple cluster of canoe-shaped folds, plunge steeply beneath the general plains surface of the northern prolongation of the Mexican tableland, never again to reappear. In marked contrast to the prevailing relief expression of the Cordillera, with its stream-cut profiles, the physiognomy beyond is that of typically enisled landscape of the desert, fashioned mainly by the winds. The chain aspect of the Rockies gives way to solitary ridges. All mountains assume the character of short, lofty ranges which, with startling abruptness, rear themselves like volcanic isles jutting from a summer sea. So thickly do these isolated piles stud the vast smooth plateau plains that Dutton aptly likens them on the map to an army of caterpillars crawling northward out of Old Mexico.

Inasmuch as the northern extension of the Mexican tableland is included mainly within the present limits of the state of New Mexico its topographical features, so far as the United States go, are in many respects quite unique. Throughout this region the areal distribution of the geological formations is probably the least understood of any considerable tract in our country. In only a few circumscribed districts is the geological structure brought out properly and correctly in mapping. Elsewhere, according to published information, the region seems to be a veritable *terra incognita*. Even the larger relationships of the formations are so little known that they have yet to be exactly determined.

Over this northern segment of the lofty tableland the general plains surface lies evenly about a mile above the sea. Towering still another mile in the air are the innumerable mountain masses. The intermontane plains being chiefly desert or semi-arid, rock outcrops are few in number; and drifting sands and mobile earths

prevail. Over such a country geological boundaries are not easily traced; and determination of the original areal distribution of the various terranes is beset with exceptional difficulties.

In most other parts of the world the local stratigraphic succession and general mapping of rock tracts are based chiefly on the rock exposures bordering the valleys of incised streams. These outcrops as a rule lie below the general upland level of the country. In the New Mexican field, the rock sections lie principally above the general plains surface. Correlative determinations of outcrops are thus exactly the reverse of what they usually are.

Disposition of the sections, a mile or more high in many instances, is that of a myriad of drill-cores set upon a board. Spaces between sections are voids in nature as in model. Under ordinary circumstances these intersectional intervals are filled up by the rock masses of the interstream areas. In order properly to visualize the geological formations of the tableland the various sections have to be connected and projected on a common plane. Such a ground plan is very different from a normal geological map. Yet it is the only kind of a diagram that satisfactorily depicts the larger relationships of the geological formations. For the region under consideration such a projection is represented in the accompanying cut (Fig. 1), the base plane selected being the ancient peneplain lying at the base of the great Pennsylvanian limestone plate.

The fact that at the southern extremity of the Rockies the Pennsylvanian limestones everywhere rest directly on pre-Cambrian schists long led to the inference that a region of continental proportions had been a land area during the greater part of Paleozoic times. Such apparently was not the case. When, a decade ago,[1] the geological formations of New Mexico were briefly described in a systematic way, a circumstance that was expressly pointed out was that while over all the northern half of the state there were no Paleozoics below the Pennsylvanian limestones, it did not preclude the existence of some, or even all, of the early periodic sections elsewhere. In fact, in southern New Mexico isolated sections of these

[1] *Report of Governor of New Mexico to Secretary of Interior for 1903*, pp. 337–41, 1904.

older rocks were incidentally noted very early. These outcrops were so widely disconnected as to give rise in some quarters to not a little doubt concerning the actual presence of some of the terranes.

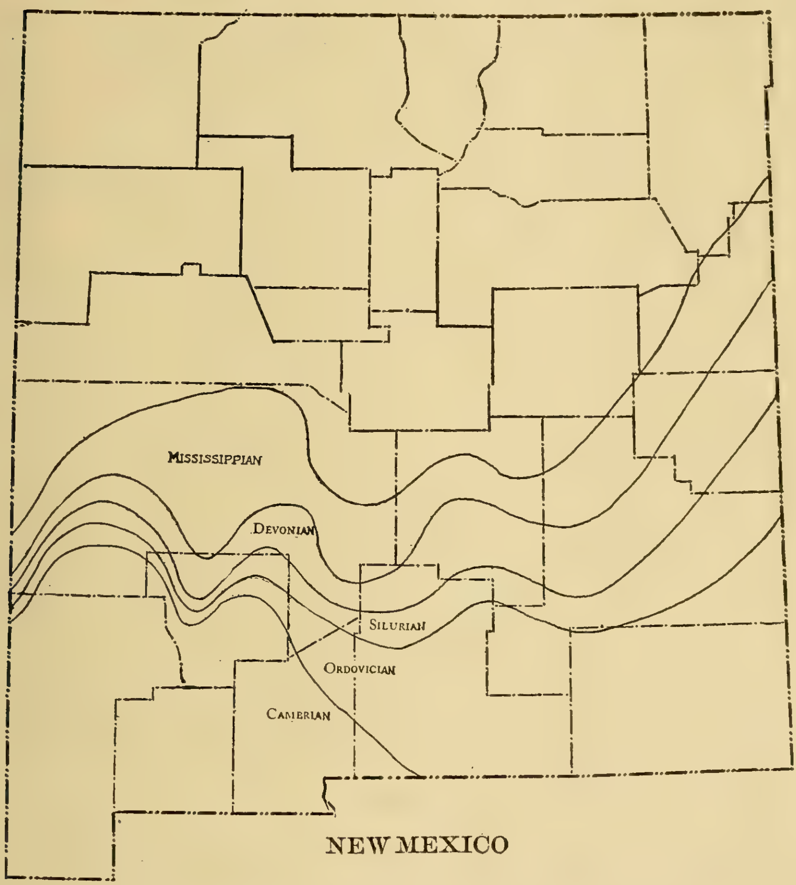

FIG. 1.—Areal distribution of Paleozoic periodic formations

Pioneer observations now seem to be fully verified. As early as 1874 Dr. W. P. Jenney[1] called attention to the presence of Cambrian rocks in the Franklin Range north of El Paso. In the same locality Dr. A. Wislizenus,[2] thirty years before, collected characteristic Ordovician fossils. Numerous organic remains of Silurian age

[1] *Proc. New York Lyc. Nat. Hist.*, Vol. II (1874), p. 69.

[2] *Memoir of Tour through Northern Mexico in 1846–47* (1848), 141 pages.

were obtained at Santa Rita, in 1873, by Professor G. K. Gilbert.[1] Devonian strata were first recorded in New Mexico by Thomas Antisell;[2] and in the following year the fossils were described from this region by Professor James Hall.[3] Mississippian forms collected by Professor E. D. Cope were described in 1881 by Mr. S. A. Miller.[4] The most northerly points at which they were recognized recently were in the Magdalena Mountains, west of Socorro,[5] and in the Sierra Ladrones 25 miles north.

So in New Mexico prior to the year 1880 all of the periodic terranes of Paleozoic age had been already fully identified.

In this tableland region the outstanding feature of the stratigraphy, and a characteristic which is perhaps nowhere else met with, is a notable segregation, instead of the usual alternation, of the hard and soft strata. Resistant beds are confined chiefly to the bottom half of the vertical section; and nearly all of the weak rocks occur only in the upper part. For a succession more than 10,000 feet in thickness this circumstance is certainly a quite remarkable one. Almost the entire Paleozoic sequence is thus composed of limestones of such uniform lithologic texture and aspect that it is not usually possible by casual glance to detect the parts of different geologic age. Only by careful discrimination of the successive faunas at the various stratigraphic levels are even the larger, or periodic, subdivisions rendered determinable. Yet, on the whole, the sequence is one of the most complete on the American continent. Out of twenty-five major terranes holding serial rank only five seem to be missing.

Both by reason of its completeness and because of its peculiar continental relationships this general geological section of the New Mexican Paleozoics is for purposes of reference one of the important successions of the country. As determined by various parties from the United States Geological Survey, and the State Geological Sur-

[1] *U.S. Geog. and Geol. Surv. W. 100th Merid.*, Vol. III (1875), p. 117.

[2] *Explo. and Surv. Pacific Railroad*, Vol. III (1856), Pt. II, p. 181.

[3] *United States and Mexican Bound. Surv.*, Vol. I (1857), Pt. II, p. 104.

[4] *Jour. Cincinnati Soc. Nat. Hist.*, Vol. IV (1881), p. 314.

[5] *Proc. Iowa Acad. Sci.*, Vol. XII (1905), p. 169.

vey, and by others who have worked more or less extensively in the region, the essential features of the section are well epitomized in recently published tables.[1]

Since it is with marked unconformity that the Paleozoics rest upon the pre-Cambrian crystallines it is evident that long before Paleozoic deposition in the region set in, the old continental complex was beveled off to a smooth plain. This ancient erosion surface cuts evenly the folded, faulted, and altered pre-Cambrian strata, the more or less highly metamorphosed clastics, and the strictly igneous masses and intrusions. It doubtless represents as true a peneplain as ever existed, and one that remained longer and nearer base level than any other one known in geological history. The presence of this once low-lying plain and the near-shore deposition of the vast piles of homogeneous limestones appear strongly to support the idea of the existence of a close genetic relationship between the two phenomena.

Notwithstanding the fact that such exceptional homogeneity prevailed throughout the Paleozoic succession of the northern Mexican tableland, no less than a dozen major unconformities attest the frequency and extent of notable diastrophic movement. Of these by far the most conspicuous hiatus is that at the base of the Pennsylvanian limestones. In every way it is the most pretentious. Its character and position associate it with the similar phenomenon displayed in the Mississippi Valley. From that it differs in the apparent absence of the Coal Measures. However, this dissimilarity fades since remnants of the latter are now known to be actually present. How extensive they originally were is yet a matter of conjecture.

In the Ladronesian series, exposed in a circumscribed basin near Socorro,[2] are represented the all but vanquished coal shales which may be the southwestern extension of the great Arkansan series of the Ozark region. The unconformity plane is comparable in every way with that found at the base of the Coal Measures of Iowa, Missouri, and Illinois. It extends far to the north in Colorado; and far to the south in Old Mexico. Although in the Rocky

[1] *Proc. Iowa Acad. Sci.*, Vol. XXII (1916), pp. 249–71.

[2] *Journal of Geology*, Vol. XII (1904), pp. 250–51.

Mountains region all strata down to the pre-Cambrian complex are removed and the Pennsylvanian limestones rest directly upon the ancient crystallines, in southern New Mexico the same limestone plate reposes on the beveled edges of all of the older and somewhat deformed Paleozoics (Fig. 2).

Certain peculiarities in the areal distribution of the Paleozoic formations in southern and central New Mexico at once raise far-reaching questions in diastrophics. Among them not the least significant is whether the northern limits of the several major terranes are approximately the original boundaries of deposition, or

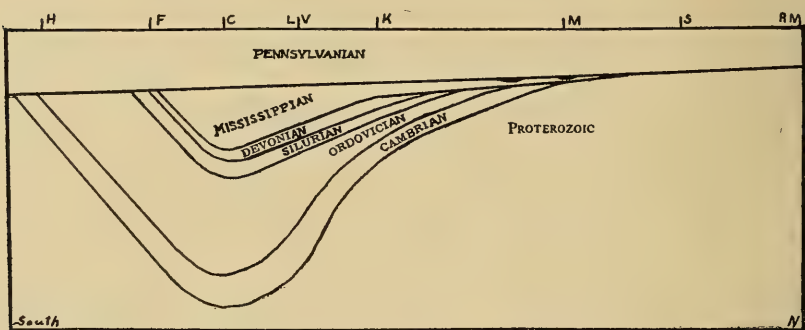

FIG. 2.—Relations of periodic formations south of Rocky Mountains

whether these periodic terranes once extended indefinitely northward over the tract which later was upraised into the Rocky Mountain arch.

Casual consideration of present conditions points sometimes to one conclusion and sometimes to the other. Critical evidence centers on the character of the marked unconformity at the base of the Pennsylvanian section. The present northern boundaries of the other periodic terranes are very close together (Fig. 1). The strata are all virtually limestones. There are practically no characteristic shore deposits represented. Positions of none of the formations indicate that there are any well-defined overlaps. All features considered, the conclusion appears inevitable that the strand oscillations at different times were of great magnitude,

amounting to hundreds of miles, instead of very short distances as at first glance seems probable.

Paleogeographical maps commonly show the southern Rocky Mountain region as a huge island persisting throughout Paleozoic times. Orographic arching of the tract appears to have taken place only late in the era. For the first time since pre-Cambrian days general peneplanation does not appear until the Mississippian or Pennsylvanian period.

That the peneplanation at the beginning of Pennsylvanian times, when Coal Measures were being deposited elsewhere around the growing American continent, was extensive is strongly supported by many facts. Since farther north in the Rocky Mountains area the older Paleozoics are present in a few limited and isolated belts, where they are preserved through infolding with more ancient rocks, it is presumed that Cambrian, Ordovician, Silurian, Devonian, and Mississippian strata as they are represented in the South doubtless once extended entirely over the province before its epeirogenic uprising. Over the Mexican tableland district last lingering traces of the old formations remained until the grand erosional period represented elsewhere to the eastward by the Arkansan (Pennsylvanian) deposition. It may be that the Pennsylvanian peneplanation epoch of the southwestern region is to be exactly paralleled with that of Iowa where it is designated as the Arkansan hiatus.

Another reason why in the Cordilleran region north of the Mexican tableland the Paleozoics do not appear more frequently than they do is that Triassic peneplanation was also profound. This surface is largely covered by mid-Cretaceous sediments before the eastern front of the Rockies is reached. Along this border the more ancient rocks are thus not open to inspection.

The rather abrupt termination of the several periodic terranes of the Paleozoic toward the north in central New Mexico does not appear to be altogether a direct result of successive advances of the ancient sea in that direction over a low-lying even coast. If any part of the abrupt thinning is thus to be ascribed it is entirely lost through repeated and profound planation effects. After the laying down of the great Pennsylvanian limestones no less than two of

these planation periods are clearly indicated by marked unconformities displayed in the general stratigraphic succession of the region. When the great peneplanation of Jurassic or early Cretaceous times took place, as marked by the basal surface of the extraordinarily widespread Dakotan sandstones, it was accompanied by extensive and diverse deformation with some display of volcanic action. So extensive was this main evening that so far south as central New Mexico the Dakotan sandstone is seen to repose upon the upturned

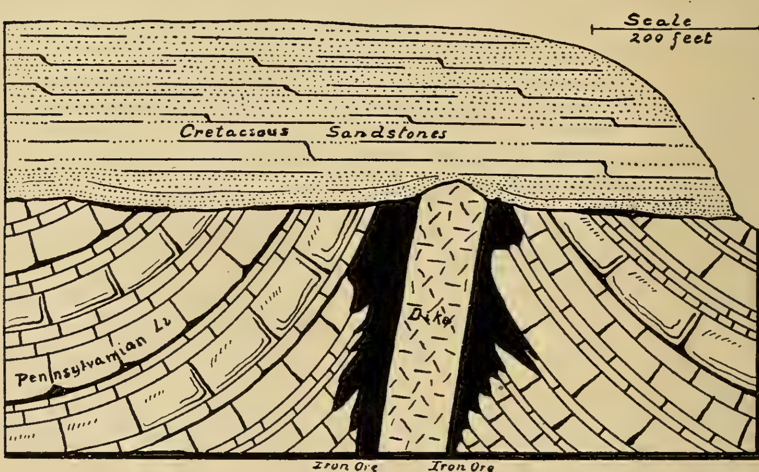

FIG. 3.—Unconformable relations of Cretaceous and Pennsylvanian beds on Chupadera Mesa, New Mexico.

and locally vertical edges of the Pennsylvanian limestones. A most notable section demonstrating these relationships is well displayed on the Chupadera Mesa, at Dios Springs, and in the Arroyo Chupadera, about thirty miles northeast of Socorro (Fig. 3).

The fancied complexity of the stratigraphy of the Mexican tableland is therefore more apparent than real. Two features in particular tend to obscure the actual mass relationships of the formations. Of these the wide separation of exposed rock sections assumes an importance out of all proportion to its difficulties or its merits. The phenomena attending diastrophic movements in the region are thus liable to serious misinterpretation. Neither the

moderate flexing nor the profound faulting are found to be so recent as to retain their impress in full force upon the present relief. These major crustal movements are mainly quite remote. Beginning at the close of Paleozoic time they continue without interruption until the present day. The effects which their supposed dominancy produces in the existing desert ranges are now known to be due entirely to other causes. On the whole the desert ranges seem to owe their physiognomy to vigorous wind erosion under the stimulus of aridity rather than to recent deformation. Under these abnormal conditions old structures are brought out into strong relief by simple differential erosion of weak and resistant rock belts. This desert degradation so vigorous at the present day may have been of long duration, having gone on since the beginning of Tertiary times.

The post-Cretaceous wrinkling of the Rocky Mountains is reflected in the areal distribution of the rock formations far beyond the southern terminus of that cordillera, reaching many miles into the Mexican tableland.

SOME ESTIMATES OF THE THICKNESS OF THE SEDIMENTARY ROCKS OF OHIO

T. M. HILLS
Ohio State University

Since the discovery of crystalline rock at a depth of 3,320 feet at Waverly[1] in 1911, and at Findlay,[1] at a depth of 2,770 feet, in 1912, deep wells have been drilled in many parts of Ohio. From their records, the following estimates are made of the thickness of the sedimentary rocks along the eastern and southern borders of the state.

The data used[2] have been taken from wells located along three lines, two of them running east-west, the other north-south. The first extends from Findlay through Cleveland eastward to the central part of Ashtabula County, the second from the city of Columbus east to northern Muskingum County, the third from Norwalk to Jefferson Township, Jackson County.

The two formations used as datum planes in the calculations are the Trenton and the Clinton. The tops of these formations are recognized with a reasonable degree of certainty by drillers. Unfortunately, the two wells mentioned above are the only ones that have passed through the Trenton rocks of the state. Therefore the distance from the top of the Trenton to the crystalline rocks must be taken from these wells and considered as constant for the area. The wells in the eastern and central parts of the state do not extend below the Clinton; therefore the depth from this formation to the Trenton, and to the crystalline rocks below, must be supplied from the known wells of other parts of the state. This assumes that the Trenton-to-crystalline-rock interval is constant over a wide area, and that the Clinton-to-Trenton interval varies at a uniform rate. These are both broad assumptions, but with the data available cannot be avoided.

[1] Condit, *Amer. Jour. Sci.*, Fourth Series, Vol. XXXVI, p. 123, August, 1913.

[2] Acknowledgments are due *The Ohio Geological Survey* for the use of its files of well data.

The northern line of wells.—At Findlay the interval between the crystalline rocks and the top of the Trenton formation is 1,605 feet. This will be considered as constant for northern Ohio.

At Lorain, the interval between the Clinton and the Trenton is 1,075 feet, at Cleveland 1,658 feet, an increase of 21 feet per mile to the eastward. If this continues to the state line sixty miles eastward, the interval would be 2,918 feet (1,658+1,260).

In Wayne Township, Ashtabula County, the Clinton formation is found 2,940 feet below sea level. Data from wells at Lorain, Avon, East Cleveland, Chester Township, Geauga County, Hartsgrove and Wayne townships, Ashtabula County, show an average, although not constant, decline of the surface of this formation of 22.7 feet per mile. If the eastward decline continues at the same rate to the state line, the surface of the formation should be about 3,172 feet below sea level at this point. Add to this figure the estimated distance between the top of the Clinton and the top of the Trenton, 2,918 feet, and the distance from the top of the Trenton to the crystalline rocks, 1,605 feet, and we have a total of 7,695 feet, the depth below sea level at which crystalline rocks should be found near the northeastern corner of Ohio. An addition of at least 1,000 feet should be made for the thickness of strata above sea level, giving a total estimate of some 8,700 feet of sedimentary rocks in this part of the state.

Central Ohio.—The wells extending from Columbus to north central Muskingum County are not on a straight line, but the departures to the north side are practically balanced by those to the south. It will be seen later that the variation in thickness of the sedimentary rocks along a north and south line is comparatively slight in short distances.

The Clinton occurs 186 feet below sea level in a well along the Mifflin Township line in the eastern part of the city of Columbus. From this well to one at Basil, the top of the Clinton declines at an average rate of 41 feet per mile. Eight other wells, some of them as far east as north central Muskingum County, show a decline ranging from 56 feet to 34.9 feet per mile, with an average of 46.6 feet. Using the last figure, the top of the Clinton should be 5,778 feet (=186+5,592) below sea level at Wheeling, 120 miles eastward.

At Waverly the top of the Clinton is 310 feet below sea level, and the top of the crystalline rocks, 2,730 feet. The interval between is 2,420 feet. If at Wheeling the interval is the same, the crystalline rocks would be found at 8,198 feet (=5,778+2,420). Add 1,000 feet for the strata above sea level, and the estimate is brought to 9,198 feet. This figure does not include the increase in the interval between the top of the Clinton and the top of the Trenton found along the northern part of the state, which was 21 feet per mile. Addition for such thickening would add 2,520 feet, bringing the total to 12,028 feet.

The north and south line of wells.—This row of wells is practically at right angles to the other two.

At Norwalk the Trenton was reached 1,945 feet below sea level. In Jefferson Township, Jackson County, it was found at 2,885 feet, a difference of 940 feet in 162 miles, a decline of 5.8 feet per mile. If this decline continues southward to the Ohio River, twenty-five miles farther, the Trenton would be found there 3,030 feet below sea level. The Trenton (top)-to-crystalline interval of 1,220 feet, found at Waverly, would place the bottom of the sedimentary rocks 4,250 feet below sea level. Add a thousand feet for strata above sea level, as in the previous cases, and we have 5,250 feet for the thickness of strata above the crystalline rocks at the Ohio River, near Ironton.

Summary.—From the northern line of wells the sedimentary strata of northeastern Ohio are estimated to be nearly 9,000 feet, from those of central Ohio to be over 12,000 feet in the eastern part of the state, and in southern Ohio to be more than 5,000 feet thick.

Wells along other lines give results of the same order of magnitude, the same assumptions concerning the interval between the top of the Trenton and the crystalline rocks being made. Since the post-Trenton strata thicken toward the Appalachian trough, either by the increase in the thickness of the formations themselves, or the introduction of new formations, it is reasonable to suppose that the pre-Trenton sediments do the same, so that the results obtained are probably underestimates rather than overestimates.

The presence of the Cincinnati Arch in the southwestern part of the state adds so many complicating features that it does not now seem advisable to attempt an estimate for this part of the state.

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Among articles to appear in early numbers of the *Journal of Geology* are the following:

Notes on Principles of Oil Accumulation. By A. W. McCoy. Discussed by Chester W. Washburne.

Reply to Discussion by C. W. Washburne on Notes on Principles of Oil Accumulation. By A. W. McCoy.

Diastrophism and the Formative Processes. XII. The Physical States of the Earth and Its Neighbors during Their Formative Stages. By T. C. Chamberlin.

Compilation and Composition of Bituminous Coals. By Reinhardt Thiessen.

Geological Setting of New Mexico. By C. R. Keyes.

Slides in the Conemaugh Formation near Morgantown, West Virginia. By Earl R. Scheffel.

Factors Producing Columnar Structure in Lavas and Its Occurrence near Melbourne, Australia. By Albert V. G. James.

Movements in Crystallizing Magma. By Frank F. Grout.

Deformation of Crystalline Magma. By N. L. Bowen.

The Chester Series in Illinois. By Stuart Weller.

The Juan de Fuca Lobe of the Cordilleran Ice Sheet. By J H. Bretz.

VOLUME XXVIII NUMBER 2

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FEBRUARY-MARCH 1920

THE ORIGIN OF GUMBOTIL

GEORGE F. KAY AND J. NEWTON PEARCE
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The name gumbotil[1] was proposed recently for clays of distinctive characters which lie on glacial till and which are related closely to till. As originally defined, gumbotil is "a gray to dark colored, thoroughly leached, non-laminated, deoxidized clay, very sticky and breaking with starchlike fracture when wet, very hard and tenacious when dry, and which is chiefly the result of weathering of drift. The name is intended to suggest the nature of the material and its origin." In Iowa there is gumbotil on the Nebraskan, Kansan, and Illinoian drifts. It has not been developed on the Iowan drift nor on the Wisconsin drift.

SOME OF THE FORMER VIEWS REGARDING THE ORIGIN OF SUPERDRIFT CLAYS

Until recently these superdrift clays which are now called gumbotils had been found only on the Kansan and Illinoian drifts, in connection with which drifts the clays had been described under the name gumbo by several geologists.

Regarding the origin of this gumbo there have been various interpretations, some of which will be outlined briefly.

[1] George F. Kay, "Gumbotil, a New Term in Pleistocene Geology," *Science*, New Series, Vol. XLIV, November 3, 1916.

The gumbo of McGee.—Dr. W J McGee applied the name gumbo to the peculiar, tenacious clay which he found on his Lower Till,[1] and in referring to the habit of weathering of this till he states:[2]

Where the clay is plastic and sand free and of the usual blue color, as in the superior peripheral portion generally, it commonly weathers whitish or ashen to a limited depth and forms a tenacious, intractable soil, drowning when wet and baking when dry. This phase is colloquially known as "gumbo," sometimes as "hardpan," and locally as "white clay," or (from its behavior below the plow) "push land."

The gumbo of Leverett.—Mr. Frank Leverett in his monograph "The Illinois Glacial Lobe" described the gumbo which he found associated with the Illinoian and Kansan drifts in southeastern Iowa.[3] He believed that the gumbo on the Illinoian drift was of the same age as that on the Kansan drift and favored the interpretation, although he was not satisfied fully with the view, that the gumbo is the result of aqueous deposition following submergence of the region.

The gumbo and loess-silt of Bain.—Dr. H. F. Bain, in his report on the geology of Decatur County, Iowa, states that blue to drab-colored gumbo which in places overlies the Kansan drift and is distinct from the drift belongs stratigraphically with the loess, and presents the view that the gumbo suggests a quiet-water deposit which has been compacted or puddled by water.[4] In earlier geological reports of counties in Iowa the same author refers to similar material. In his report on Keokuk County, Iowa, he refers to a stiff, yellow to blue-gray, plastic, non-calcareous clay which is on the Kansan drift and beneath the loess on the uplands, and states:[5] "It seems to be a deposit closely akin to the loess and

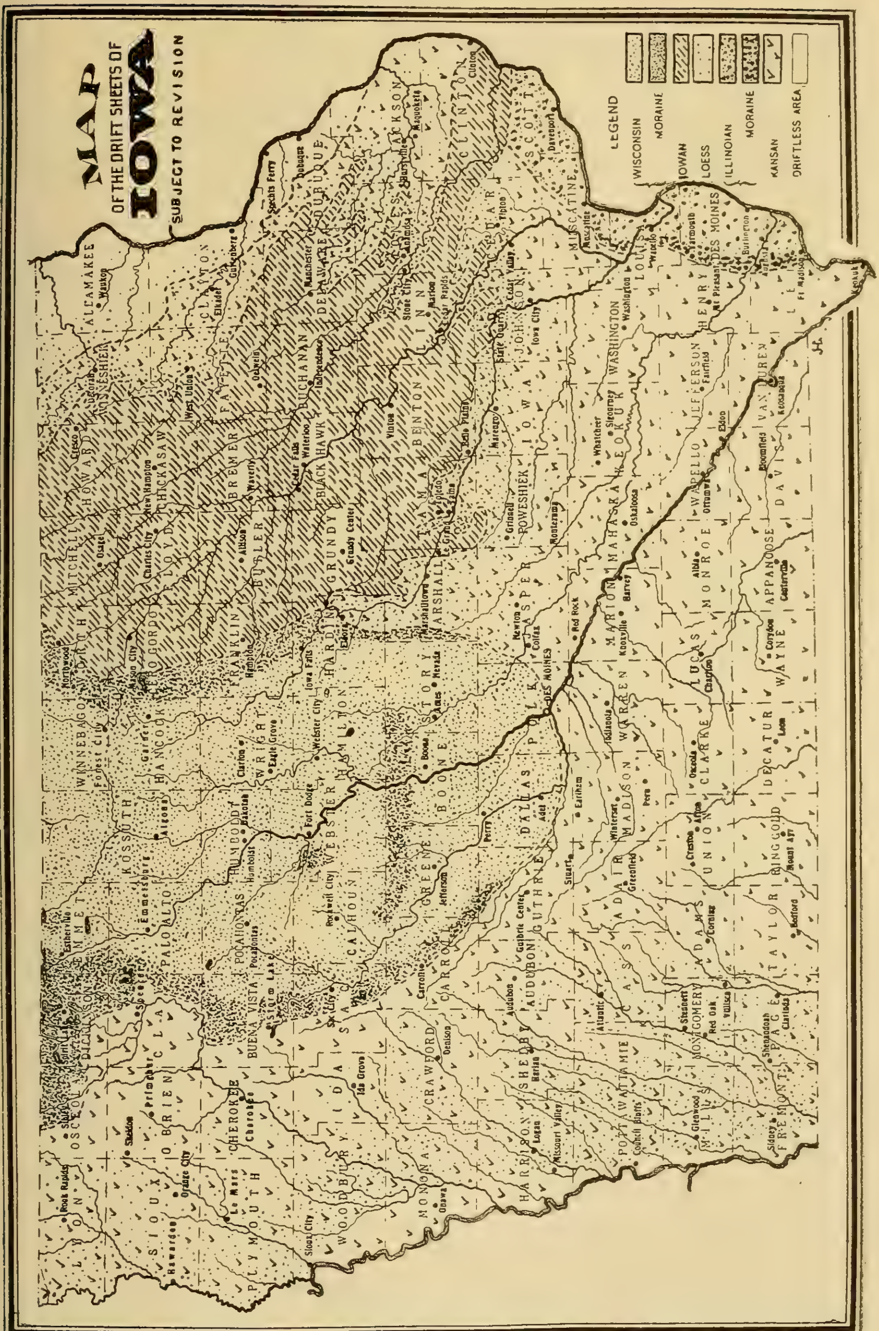
[1] Kansan drift of present classification.

[2] W J McGee, "The Pleistocene History of Northeastern Iowa," *U.S. Geol. Surv., Eleventh Ann. Rept.*, Part I (1891), p. 509.

[3] Frank Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Surv.*, Monograph XXXVIII (1899), pp. 28–33.

[4] H. F. Bain, "Geology of Decatur County, Iowa," *Iowa Geol. Surv.*, Vol. VIII (1897), p. 292.

[5] H. F. Bain, "Geology of Keokuk County, Iowa," *Iowa Geol. Surv.*, Vol. IV (1894), p. 302.


MAP
OF THE DRIFT SHEETS OF
IOWA
SUBJECT TO REVISION
LEGEND
WISCONSIN
MORAINE
IOWAN
LOESS
ILLINOIAN
MORAINE
KANSAN
DRIFTLESS AREA

probably genetically related to it. Very likely it is but a phase of that deposit though differing from it in its plasticity, color, and density." In his report on Appanoose County, Iowa, Dr. Bain describes a loess-silt[1] on Kansan drift which he considers to have been deposited later than the drift, and which in character and origin seems much like the white clays of Ohio Valley described by Leverett.[2]

In a geological report on Madison County, Iowa, Dr. H. F. Bain and Dr. J. L. Tilton refer to a dark-colored, impervious, unfossiliferous clay on Kansan drift as the lower of two phases of loess in the county.[3]

The gumbo of Udden.—Mr. J. A. Udden in a report on the geology of Pottawattamie County, Iowa, describes in considerable detail the gumbo or red clay associated with drift and makes the following statement regarding its origin:[4]

> It would be premature at the present time to express any opinion as to the origin of this deposit. Probably it is mostly an old loess, which has been clogged up by interstitial deposition of fine ferruginous material through the agency of the ground water. Perhaps it is in part a fluviatile deposit, made at a stage of semi-stagnant drainage, or possibly it is of varied origin, being in some places a surface wash, or a disintegration product derived from an underlying bowlder clay, and at other places a modified upland loess, or a river silt.

The Dallas formation of Tilton.—Dr. J. L. Tilton gave the name Dallas deposits to gumbo and related materials overlying Kansan drift in southern Iowa. He considered the deposits to have been formed during the closing stages of the Kansan glacial epoch.[5]

The gumbo of Arey.—In a report on the geology of Davis County, Iowa, Professor M. F. Arey states that the gumbo which lies on the Kansan drift is perhaps a water deposit.[6]

[1] H. F. Bain, "Geology of Appanoose County, Iowa," *Iowa Geol. Surv.*, Vol. V (1895), pp. 407–8.

[2] Frank Leverett, "On the Significance of the White Clays of the Ohio Region," *American Geologist*, Vol. X (1892), pp. 18–24.

[3] H. F. Bain and J. L. Tilton, "Geology of Madison County, Iowa," *Iowa Geol. Surv.*, Vol. VII (1896), p. 523.

[4] J. A. Udden, "Geology of Pottawattamie County, Iowa," *Iowa Geol. Surv.*, Vol. XI (1900), p. 258.

[5] J. L. Tilton, "A Pleistocene Section from Des Moines South to Allerton," *Iowa Acad. of Science*, Vol. XX (1913), pp. 218–20.

[6] M. F. Arey, "Geology of Davis County," *Iowa Geol. Surv.*, Vol. XX (1909), p. 511.

The Loveland of Shimek.—Professor B. Shimek proposed the name Loveland formation[1] for gumbo-like deposits related to Kansan drift in Harrison, Monona, and adjacent counties in southwestern Iowa. Detailed descriptions of the formation are given in his report on the geology of Harrison and Monona counties.[2] Here he refers to the fact that Mr. Udden described similar material in Pottawattamie County as gumbo or red clay. It should be pointed out that the Loveland of Shimek differs in some important respects from the Kansan gumbotil of southern Iowa. The gumbotil is found only on glacial till and has a definite topographic position. According to Professor Shimek the Loveland in places lies not on till but on gravels. Moreover, it is not confined to a particular stratigraphic plain; the term has been applied to material in the lower part of the bluffs along the Missouri River in some places as well as to material 180 feet higher than the bases of the bluffs. Shimek considers the Loveland formation to be a water deposit which was formed during the stage of melting of the Kansan ice, and which has the same relation in general to the Kansan drift as have the Buchanan gravels to Kansan drift. This interpretation may, however, be somewhat open to question, as recent studies indicate.

The super-Kansan gumbo of Alden and Leighton.—In a recent publication by Dr. W. C. Alden and Dr. M. M. Leighton there is a discussion of super-Kansan gumbo in Iowa. The authors do not commit themselves definitely with regard to its origin, but they present evidence which they consider favorable to the view advanced by Kay that the gumbo is the residuum of thorough weathering and long leaching of the upper part of the Kansan till.[3]

Sufficient evidence has been submitted to show clearly that the students of superdrift clays—the gumbotils and related materials—have been far from agreement regarding their origin. Some geologists have considered these clays to be mainly of fluvioglacial origin, others believe that they are aqueous, and still others have

[1] B. Shimek, "Aftonian Sands and Gravels in Western Iowa," *Bull., Geol. Soc. Amer.*, Vol. XX (1910), p. 405.

[2] B. Shimek, "Geology of Harrison and Monona Counties," *Iowa Geol. Surv.*, Vol. XX (1909), pp. 371–75.

[3] W. C. Alden and M. M. Leighton, "The Iowan Drift," *Iowa Geol. Surv.*, Vol. XXVI (1915), p. 91.

thought them to be related to loess. Until recently McGee was the only geologist who had stated definitely that the material which is now called gumbotil is the product of weathering of drift.

FIELD STUDIES OF GUMBOTILS AND RELATED MATERIALS

The conclusion which was presented by Kay in his paper in *Science* is:

> . . . . that the gumbotil is the result chiefly of the chemical weathering of drift was reached only after the field relations of gumbotil had been studied carefully, and detailed chemical analyses of Nebraskan gumbotil, Kansan gumbotil, Illinoian gumbotil, and the glacial tills underlying these gumbotils had been made.

The field relations of Kansan gumbotil to the underlying Kansan till have been already briefly described.[1] The Kansan gumbotil, there called super-Kansan gumbo, reaches a maximum thickness of more than twenty feet, and is limited to tabular divides and other remnants of a gumbotil plain which, before it was affected by erosion, was as extensive, apparently, as the original Kansan drift plain. This gumbotil occupies a definite topographic position, and where it is exposed in railroad cuts it is seen to lie horizontally in the cut and not to conform to the surface slopes which have been developed by erosion. The gumbotil is dense, sticky, and very slippery when wet, but is hard and very tenacious when dry. It is usually dull gray to drab in color; in places the gray color is mottled with brown and reddish tints. It is leached, but in many places it contains lime concretions. The dry surfaces of the exposures of gumbotil are distinctly checked by sun cracks. It contains only a few small, scattered pebbles, which consist predominantly of quartz and chert and subordinately of crystallines and quartzites. A striking feature of the quartz and chert pebbles is their remarkably smooth surfaces. The gumbotil grades downward into yellowish to chocolate-colored till, in many places with numerous pebbles, few if any of which are calcareous. This oxidized and non-calcareous till, in turn, merges into unleached

[1] George F. Kay, "Some Features of the Kansan Drift in Southern Iowa," *Bull., Geol. Soc. Amer.*, Vol. XXVII, pp. 115–17; reprinted in *Iowa Geol. Surv.*, Vol. XXV, pp. 612–15.

till, oxidized yellowish for several feet vertically, below which is the normal, unoxidized and unleached, dark grayish to bluish-black Kansan till. An impressive feature of the unleached, oxidized till is the presence of numerous concretions of calcium carbonate, the lime of the concretions having been dissolved in connection with the formation of the overlying gumbotil and leached till, carried downward and later precipitated.

Some sections showing the relations of Kansan gumbotil to underlying Kansan drift.—The following sections are given as typical of many sections that have been studied at widely separated places in the Kansan-drift areas of Iowa. They are intended to show the intimate field relations of the Kansan gumbotil to the underlying till.

Section in cut on the Chicago, Milwaukee & St. Paul Railway about one mile east of Foster Station, in the southeast corner of Monroe County, Iowa:

	Feet	Inches
5. Soil, black, porous	2	
4. Loesslike clay, chocolate-colored, leached	1	6
3. Loesslike clay, light-colored, grayish; on dry surface looks like gumbotil; has chocolate-colored stains; sticky when wet; contains a few small siliceous pebbles; leached	5	6
2. Gumbotil (Kansan), gray-colored, in lower part chocolate-colored; few pebbles; starch-like fracture when wet; leached	12	
1. Glacial till (Kansan), brown color, with very irregular patches of gray-colored till resembling gumbotil; dry surface of the till is brownish yellow; damp surface is chocolate-colored; few pebbles; leached to base of cut	5	

Section in cut on the Chicago, Burlington & Quincy Railway at mile 372, one mile west of Murray Station, Clarke County, Iowa:

	Feet
4. Loesslike clay, gray to pale-yellowish color, with irregular lines of brown on dry surface; when damp it is grayish with mottling of yellow to brown colors; stands vertically, upper few feet mealy	15

	Feet
3. Gumbotil (Kansan), gray to drab in color, sticky when wet, hard and tenacious when dry; contains a few siliceous pebbles; leached	11
2. Glacial till (Kansan), oxidized and leached..	4
1. Glacial till (Kansan), oxidized and unleached; has many lime concretions..................	11

Section in cut on Chicago, Milwaukee & St. Paul Railway no the divide about three miles west of Templeton, Carroll County, Iowa:

	Feet	Inches
4. Loess		
Buff-colored, leached....................	15	
Buff-colored, unleached..................	10	
3. Gumbotil (Kansan), gray to dark-drab to chocolate-colored, upper few feet reddish, a few small siliceous pebbles	20	6
2. Glacial till (Kansan), oxidized yellow to buff, leached, closely related to No. 3............	7	
1. Glacial till (Kansan), oxidized, unleached; many calcareous concretions..............	8	

Section in cut on Santa Fe Railway east of New Boston, Lee County, Iowa:

	Feet
4. Loesslike clay, top 2 feet very light gray; below, yellow to light-brown on dry surface; when freshly cut into, more chocolate-colored; a joint clay; grades into No. 3.............	12
3. Gumbotil (Kansan), typical; gray on dry surface and has a checked appearance; when freshly cut into, has a more drab color; very sticky; contains some spots of brown; contains small siliceous pebbles; leached; grades into No. 2..............................	12
2. Glacial till (Kansan), oxidized and leached; contains patches of gray similar to the gumbotil; many pebbles; grades into No. 1....	5
1. Glacial till (Kansan), oxidized and unleached; contains many pebbles and small bowlders; many calcareous concretions; to the bottom of the cut, exposed..........................	27

In all of these sections the zone of oxidized and leached till beneath the gumbotil is narrow. A study of thirty-five sections widely separated as to location shows that in eighteen of them the zone of oxidized and leached Kansan till beneath the Kansan gumbotil is 5 feet. In twelve of them it is 5 feet 6 inches; in the remaining sections the zone is somewhat more than 5 feet 6 inches or slightly less than 5 feet. The uniform thickness of the leached zone is impressive. The thickness of the oxidized, unleached zone of Kansan till is about 40 feet.

The distribution of Kansan gumbotil in Iowa.—The relations of Kansan gumbotil to the underlying Kansan till have been seen at scores of places in southern Iowa and at many places in other parts of the state. In fact the Kansan gumbotil has been studied in every county of three tiers of counties in southern Iowa as well as in many of the counties which are farther north.[1] Moreover, within the Iowan-drift area the Kansan gumbotil has been found beneath Iowan drift at numerous places.[2] It will be of interest to state that the Kansan gumbotil is now known at a sufficient number of places in Iowa to permit the restoration of the Kansan gumbotil plain, that is, the original plain surface of the weathered Kansan till, as it was in Iowa before any great erosion was accomplished.

Some sections showing the relations of Nebraskan gumbotil to underlying Nebraskan drift.—The field relations of the Nebraskan gumbotil to the underlying Nebraskan till are similar to the relations that have been described as existing between the Kansan gumbotil and the underlying Kansan till. The two tills, the Nebraskan and the Kansan, are much alike lithologically and both appear to have undergone similar changes under similar conditions. Below the Nebraskan gumbotil there is, as in the case of the Kansan gumbotil, a narrow zone of leached, oxidized till which grades downward into unleached, oxidized till with many concretions.

[1] George F. Kay, "Pleistocene Deposits between Manilla in Crawford County and Coon Rapids in Carroll County, Iowa," *Iowa Geol. Surv.*, Vol. XXVI (1917), pp. 215–31.

[2] W. C. Alden and M. M. Leighton, "The Iowan Drift, a Review of the Evidences of the Iowan Stage of Glaciation," *Iowa Geol. Surv.*, Vol. XXVI (1917), pp. 92–109.

A good section to show the field relations of the Nebraskan gumbotil to the underlying Nebraskan till is a railroad cut just east of a viaduct $1\frac{1}{2}$ miles west of Manning, Carroll County, Iowa.[1] From the surface the cut shows loess, Kansan till, soil band, Nebraskan gumbotil, and Nebraskan till. The section is as follows:

	Feet	Inches
6. Loess:		
Leached, yellowish-gray on dry surface; yellowish-brown to buff-brown on damp surface; no shells or concretions...........	7	
Unleached, lighter-colored on dry surface than the leached loess, and when damp is buff with gray streaks; contains shells and concretions........................	5	
5. Glacial till (Kansan), yellow, unleached, with calcareous concretions; numerous pebbles including granites, quartzites, etc. Below the oxidized, unleached till is gray till with a few pebbles. It is gumbotil-like, but effervesces freely. It was probably picked up from the gumbotil zone below..............	5	
4. Soil band containing carbonaceous material..		4
3. Gumbotil (Nebraskan), gray to drab-colored, few pebbles. The upper 6 feet is fine grained, gray, and is less sticky and gumbotil-like than the lower 7 feet, which is leached but has some calcareous concretions................	13	
2. Glacial till (Nebraskan), oxidized, apparently leached, but has calcareous concretions, upon which are films of manganese dioxide........	2	
1. Glacial till (Nebraskan), unleached, oxidized, light-yellowish color on dry surface, mottled brownish with gray when damp; many calcareous concretions, especially in upper 10 feet....................................	17	

In Taylor County, Iowa, at a stream crossing just west of Conway Station on the Chicago, Burlington & Quincy Railway, is an exposure at which the following section was observed:

[1] George F. Kay, "Pleistocene Deposits between Manilla in Crawford County and Coon Rapids in Carroll County, Iowa," *Iowa Geol. Surv.*, Vol. XXVI (1917), p. 225.

	Feet	Inches
4. Loesslike clay	1	
3. Gumbotil (Nebraskan), grayish to drab on dry surface; when damp, is grayish to brownish; a few siliceous pebbles; leached	11	
2. Glacial till (Nebraskan), oxidized and leached, many disintegrated bowlders	4	6
1. Glacial till (Nebraskan), oxidized, unleached, concretions, exposed	3	

Near this exposure Kansan till overlies the Nebraskan gumbotil.

Another interesting cut which shows Nebraskan gumbotil and underlying drift is along the wagon road west of Osceola, Clarke County, southwest corner of section 13, Ward Township, in front of a schoolhouse. The section is as follows:

	Feet	Inches
5. Loesslike clay, gray to light-yellow	8	
4. Glacial till (Kansan), oxidized, leached, ferretto zone on top	5	6
3. Glacial till (Kansan), oxidized, unleached, many concretions	8	
2. Gumbotil (Nebraskan), gray to drab-colored, sticky when wet, tough when dry, some calcareous concretions, a few siliceous pebbles; leached	10	
1. Glacial till (Nebraskan), oxidized, unleached; except in narrow upper zone, many calcareous concretions; bowlders and pebbles; above base of exposure	25	

Southeast of New Market and near the middle of the north boundary of section 5, Mason Township, Taylor County, Iowa, is a fine exposure of Nebraskan gumbotil with Kansan drift above it and Nebraskan drift below it. The section is as follows:

	Feet
4. Drift (Kansan), oxidized and unleached, many concretions	15
3. Gumbotil (Nebraskan), gray to drab-colored, leached, a few siliceous pebbles	8
2. Glacial till (Nebraskan), oxidized, leached	3
1. Glacial till (Nebraskan), oxidized, unleached, many calcareous concretions, exposed	22

The distribution of Nebraskan gumbotil in Iowa.—The Nebraskan gumbotil has been found in widely separated localities in Iowa. Among the many counties in which it has been studied are Decatur, Clarke, Warren, Madison, Union, Ringgold, Taylor, Adams, Adair, Cass, Montgomery, Page, Shelby, Crawford, Carroll, Tama, and Johnson counties. The topographic positions of the several outcrops indicate that the Nebraskan gumbotil was formed on an extensive plain with slight relief just as in the case of the formation of the Kansan gumbotil. The maximum thickness of Nebraskan gumbotil thus far studied is about thirteen feet. The zone of oxidation of the Nebraskan drift is rarely fully exposed; depths of oxidation of more than forty feet have been seen without the base of the zone of oxidation having been revealed.

Some sections showing the relations of Illinoian gumbotil to underlying Illinoian drift.—That the relations of the Illinoian gumbotil to the underlying Illinoian till are similar to the relations of Kansan and Nebraskan gumbotils to their respective tills may be shown by presenting two sections from many sections which are known to show similar relationships.

An exposure at the head of a ravine about one hundred yards north of the edge of the bluff north of Fort Madison, Lee County, gives a section as follows:

	Feet	Inches
4. Loess and loesslike clay, grayish-yellow to buff-yellow in color	7	
3. Gumbotil (Illinoian), drab to chocolate to dark color, starchlike fracture, few pebbles, leached; grades into No. 2	4	6
2. Glacial till (Illinoian), oxidized, leached	6	
1. Glacial till (Illinoian), oxidized, unleached to base of gulch	15	

A splendid section to show, not only the Illinoian gumbotil and underlying Illinoian drift, but also the Kansan gumbotil and underlying Kansan drift, is a railroad cut on the Chicago, Milwaukee & St. Paul Railway between Fort Madison and Sawyer, in Lee County. The cut is in section 28, Washington Township, and shows the following materials:

	Feet	Inches
6. Gumbotil (Illinoian), gray to ashen-color on dry surface; on fresh surface, gray mottled with brown; small pebbles; leached; grades into No. 5	4	6
5. Glacial till (Illinoian), oxidized brownish, contains bowlders, leached	5	6
4. Glacial till (Illinoian), oxidized, unleached, has concretions, breaks into irregular shaped fragments	1	
3. Gumbotil (Kansan), drab to dark color, starchlike fracture, some calcareous concretions; few pebbles; leached; grades into No. 2	8	6
2. Glacial till (Kansan), oxidized, pebbles and bowlders, leached	5	
1. Glacial till (Kansan), oxidized, unleached, many concretions, breaks with irregular fracture, exposed	12	

The transition zone between gumbotil and the base of the oxidized leached drift.—Many interesting sections might be given to show disintegrated and decomposed bowlders in the transition zone between gumbotil and the base of underlying leached and oxidized till. For example, on the east-west wagon road in section 1, Otter Creek Township, Lucas County, Iowa, there is in the transition zone between the Kansan gumbotil and the base of the leached, oxidized Kansan till a granite bowlder with dimensions of 4×2 feet on the slope. It is so thoroughly weathered that its outlines are discerned only with difficulty. Again, in a cut through the upland $\frac{1}{4}$ mile north of Forbush on the interurban railway between Centerville and Moravia, Appanoose County, Iowa, there is in the transition zone between Kansan gumbotil and the base of the oxidized, leached Kansan till a completely disintegrated granite bowlder 5 feet long by 2 feet wide as exposed on the surface.

The pebble content of gumbotil and underlying drift.—The gumbotils and underlying tills were studied also with regard to their pebble content to ascertain whether or not additional evidence could be obtained to strengthen the view that the gumbotils are the result of changes in what was originally till.

The average pebble content of Kansan gumbotil gained from eight analyses of pebbles made in widely separated areas in Iowa is as follows:

	Percentage
Quartz	48.5
Chert, flint, etc.	31.8
Quartzite	6.8
Granite	7.8
Basalt and greenstone	2.9
Feldspar	1.0
Sandstone	0.5

It will be seen that more than 87 per cent of the pebbles are of siliceous material; the highest percentage of siliceous pebbles shown by any of the exposures of Kansan gumbotil subjected to study was 98 per cent, the lowest 75 per cent.

The average pebble content of the leached and oxidized Kansan till beneath the Kansan gumbotil is as follows:

	Percentage
Quartz	16.8
Chert, flint, etc.	16.5
Quartzite	8.0
Granite	20.3
Basalt and greenstone	24.5
Feldspar	1.0
Felsite	7.0
Sandstone	1.0
Shale	0.6
Quartz porphyry	0.5
Schist	2.3
Gneiss	0.3

The average content of siliceous pebbles is here only about 42 per cent, compared with 87 per cent in the Kansan gumbotil; the highest siliceous content was about 55 per cent, the lowest about 25 per cent.

A study of the pebble content of the unleached and oxidized Kansan till beneath the leached and oxidized Kansan till gave an average result as follows, seven analyses being used:

	Percentage
Quartz	6.4
Chert, flint, etc.	8.3
Quartzite	3.0

	Percentage
Limestone	40.0
Granite	11.0
Basalt and greenstone	27.0
Felsite	3.0
Sandstone	1.0
Slate	0.4
Schist	0.4

It is clearly seen that the content of siliceous pebbles of the unleached and oxidized Kansan till is considerably less than that of the leached and oxidized Kansan till, the average siliceous content of the former being less than 20 per cent.

It is of interest to note that the kinds of pebbles found in the different zones of material are much alike. Of course limestone is in the unleached zone only.

Similar results were obtained when the Nebraskan and Illinoian gumbotils and their respective underlying tills were studied. For instance, the average pebble content obtained from several analyses of Nebraskan gumbotil is as follows:

	Percentage
Quartz	36.75
Chert, flint, etc.	21.25
Quartzite	20.25
Granite	8.25
Basalt and greenstone	11.0
Feldspar	1.25
Felsite	0.50

The content of siliceous pebbles is here more than 78 per cent; none of the Nebraskan gumbotil examined gave less than 72 per cent, and the highest gave 88 per cent. The studies of leached and oxidized Nebraskan till gave about 38 per cent of siliceous pebbles, and the unleached and oxidized Nebraskan till gave about 15 per cent of siliceous pebbles.

Analyses of the pebbles of Illinoian gumbotil gave an average result as follows:

	Percentage
Quartz	43
Chert, flint, etc.	53
Quartzite	..
Granite	..
Basalt and greenstone	2
Sandstone	2

Analyses of pebbles of leached and oxidized Illinoian till beneath Illinoian gumbotil gave results as follows:

	Percentage
Quartz	28
Chert, flint, etc.	38
Quartzite	..
Granite	12
Basalt and greenstone	14
Feldspar	2
Felsite	5
Sandstone	1

These analyses show also that the percentage of siliceous pebbles in the gumbotil is much higher than that in the oxidized and leached till which underlies it.

The sizes of pebbles in gumbotil and underlying drift.—When pebbles from the gumbotils and underlying tills were being taken in the field the only purpose in mind was to ascertain the percentage content of the different constituents. Later, when these studies were being made in the laboratory, it became evident that the pebbles might also be used in estimating the relative sizes of the pebbles in the different horizons, and in determining the shapes of the pebbles.

One hundred pebbles collected from the Nebraskan gumbotil at one locality had dimensions as follows: largest pebble $2.4\times1.4\times1$ cm., smallest pebble 2 mm., and average pebble 8×5 mm. The shapes of these pebbles were subangular to spheroidal. The unleached and oxidized Nebraskan drift beneath the Nebraskan gumbotil had pebbles with dimensions as follows: largest pebble $6.25\times4.5\times1.75$ cm., smallest pebble 3×4 mm., and average pebble $1.75\times1.5\times1$ cm. The pebbles were chiefly flat and subangular; some were slightly rounded.

The largest pebble in the Nebraskan gumbotil from another locality was $10\times7\times5$ mm., the smallest 1.5×2 mm., and the average 3 mm.; the shapes were subangular to spheroidal. Here the underlying Nebraskan till had pebbles, the largest pebble of which was $5.5\times3.5\times3$ cm., the smallest pebble 3×2 mm., and the average pebble $1.5\times1\times.75$ cm. The shapes of the pebbles were subangular to more or less flat.

Similar studies made of pebbles taken from Kansan gumbotil and from underlying Kansan drift gave results as follows: largest pebble in gumbotil 3.2 cm., smallest pebble 3 mm., and average pebble 7 mm. In the underlying drift there are many pebbles 10–12 cm. in diameter, a few more than 3 cm. in diameter; the smallest pebble seen was 7 mm., and the average of one hundred pebbles collected was about 1.8 cm. The shapes of the pebbles were similar to corresponding horizons in the Nebraskan materials.

CHEMICAL STUDIES OF GUMBOTIL AND RELATED MATERIALS

In addition to a study of the field relations of Nebraskan gumbotil, Kansan gumbotil, and Illinoian gumbotil, the tills which underlie these gumbotils, and laboratory studies of the physical properties of these materials, there were made detailed chemical analyses of gumbotils and related materials. The specimens were taken from exposures which had been studied carefully in the field, and the materials selected were thought to represent satisfactorily the compositions of the zones from which they were taken. The analyses were made from 1-gm. samples of fine material which had been separated carefully from pebbles and concretions. Only the material which could be sifted through a "twenty-mesh" copper-gauze sieve was pulverized and subjected to chemical analysis. Accurate determinations were limited to the oxides of aluminum, silicon, iron, calcium, and magnesium, since deductions as to the nature of the chemical processes involved in the transformation of the drift can be made only upon the proportions of these less mobile constituents now present. The analyses were made in strict accord with the preferred methods and the recommendations prescribed by Hildebrand.[1]

Before referring in detail to the kinds of materials which were analyzed, the localities from which they were taken, and the results of the analyses, it seems well to discuss somewhat fully some of the geo-physico-chemical factors which need to be understood in order to interpret correctly whether or not a material such as gumbotil is the product of weathering of till. Chemical evidence will be presented to support the field evidence that the

[1] Hildebrand, "The Analysis of Silicate and Carbonate Rocks," *U.S. Geol. Surv., Bulletin 422.*

gumbotils and underlying oxidized and leached tills have been formed by chemical weathering and leaching of till which was originally unoxidized and unleached.

The abundant field evidence supporting this theory has been presented. Emphasis has been put upon the gradation of gumbotil into underlying till, the variations in the sizes of pebbles in the related zones, and the presence of remnants of thoroughly disintegrated and decomposed bowlders in the transition zone between gumbotil and oxidized and unleached till.

There have been profound changes involving chemical processes which operated during immense lengths of time, and which occurred long ages ago. These chemical processes are subject to a few definite, general physical laws of nature which are independent of time or place. The laws of stress and strain, of the degradation of energy, of hydrolysis, of mass-action, or of solution in general are as lasting as the universe itself.

The rôle of water in geochemical changes.—The dominant factor in all of these geo-physico-chemical changes is water, more especially the aerated water. When the rain falls upon the ground one part, the "run-off,"[1] flows over the surface and escapes by way of the natural drainage channels. It is this form which produces erosion. A second part, the "fly-off," immediately evaporates into the air, while the third part, the "cut-off," penetrating the soil by way of the soil interstices, flows downward under the influence of gravity. Of these the cut-off water is the only form which is directly effective in geochemical transformations. It moves through the soil and its substrata with comparative rapidity, reappearing elsewhere as seepage water or as springs.

The rain and surface waters contain dissolved oxygen, nitrogen, and carbon dioxide, each in proportion to its partial pressure in the atmosphere. The chemical and physical processes which are continually taking place below the surface involve the absorption and formation of carbon dioxide and the disappearance of oxygen and nitrogen. These gases impart to the soil an atmosphere, and their concentrations in the soil solution follow more or less slowly the barometric changes above the surface. The soil bacteria and

[1] This terminology was proposed by McGee.

other lower forms of life are likewise producing change and undergoing change continually.

According to Cameron[1] the water within the soil is in reality of two kinds, namely, "film" water and "free" water. When a relatively small quantity of water is added to an absolutely dry soil or powdered solid there is some shrinkage in the apparent volume of the solid; the water spreads over the surface in the form of a film. With further addition of water the apparent volume of the solid material increases until a maximum is reached. The optimum water content which gives the maximum volume is a definite, critical, physical, characteristic property for a given soil or solid. A further addition of water will not increase the thickness of the soil film but will produce free-water in the soil interstices.

These two kinds of water play an important rôle. The film-water is tenaciously held by the soil and subsoil particles. In dry seasons it is practically a saturated solution of the dissolved rock and soil materials. When the surface of the ground becomes flooded, as in wet seasons or during heavy rains, the downward-moving free-water extracts and carries away a part of the mineral content of the film solution. Obviously the proportions of water-soluble materials in soils containing moving free-water should be, and are, less than those in soils containing only film-water. This was conclusively shown by Hilgard.[2] In the humid regions there is a greater amount of rainfall, hence a greater amount of downward-moving free-water, consequently a greater amount of leaching.

Once the free-water is removed the saturation of the film-water repeats. In this film-water are the dissolved rock materials, the carbon dioxide, the oxygen, the nitrogen, the soluble humous material, and the soil bacteria. Between these are evolved all of the processes leading to the disintegration of the rock material and the formation of the soil and its substrata.

Chemical nature of glacial materials.—The rock materials transported by the glaciers consisted chiefly of silicates, quartz, some clays, and other previously weathered materials. The complex silicates are salts of a very weak acid—silicic acid, with various

[1] Cameron, *Jour. Phys. Chem.*, Vol. XIV (1910), p. 340.

[2] See Merrill's *Rock Weathering and Soils*, p. 368.

base-forming metals, like sodium, potassium, calcium, magnesium, iron, and aluminium. These silicates are only very slightly soluble in water. While the amount dissolved may be exceedingly slight, it is nevertheless sufficient for the purposes here involved, if the time allowed is sufficiently long. For a given rock material the solubility, and hence the speed, of the weathering process increases with increasing fineness of the particles. Hence the fineness of the glacier flour renders it peculiarly suitable for rapid chemical conversion.

Like all salts of weak acids with strong bases, these silicates when dissolved react chemically with water, that is, hydrolyze, to form the free more or less ionized bases—the soluble hydroxides of sodium and potassium, the less soluble hydroxides of calcium and magnesium, the relatively insoluble hydroxide of iron, and either the free un-ionized silicic acid or some simple silicates. These simpler silicates continue to hydrolyze, if the reaction products are removed. There results the liberation of still other bases and in the end still simpler silicates, possibly kaolin, or even silica as quartz or sand.

If the reaction products are not removed by leaching, the dissolved materials soon attain a state of solution equilibrium. Under these conditions the decomposition products of one rock material may react with those of another to form more or less complex silicates of a secondary origin. Let the saturated solution be removed and fresh water added, the various solution equilibria are disturbed and the solution processes begin again.

The solution and subsequent hydrolysis of rock material, and the chemical reactions involved.—In the soil solution thus formed the dissolved materials will at the proper concentrations react with the carbon dioxide of the soil atmosphere to form the soluble, easily hydrolyzable carbonates of sodium and potassium and the slightly soluble carbonates of calcium and magnesium. These slightly soluble carbonates crystallize out as calcareous concretions, so frequently found in the clay subsoils. In the presence of an excess of carbon dioxide these insoluble carbonates pass into the soluble acid-carbonates and are leached away by the downward-moving free-water to lower depths, where they are again deposited in the form of concretions.

Ferrous silicates upon hydrolysis give ferrous ions. These may react with other ions of the soil solution to form the slightly soluble ferrous hydroxide or carbonate, or, what is more probable still, they may be immediately oxidized to ferric ions by the dissolved oxygen and then precipitated as the insoluble hydrated ferric oxide or basic carbonate.

Some may raise the question as to the possibility of the oxidation of the iron below the surface and out of contact with the air above. It must not be forgotten that by virtue of diffusion not only oxygen but also other dissolved gases tend to go just as far as the water does. Except at points where organic matter is undergoing decay, it is very doubtful if more than minimal traces of secondary ferrous compounds exist within or beneath the soil.

Crystalloids and colloids.—The resulting so-called weathering products may be grouped into two great general classes, namely, crystalloids and colloids. Crystalloids include all of the soluble acids, bases, and salts. They are simple in structure, that is, they exist in the dissolved state either as molecules or as ions. They are characterized by a relatively high diffusion speed and by the power to pass, though more or less slowly, through colloidal membranes. Nor is the colloidal membrane lacking in the soil; the clay itself may be considered as such a membrane.

Generally speaking, the term colloid is applied to all glue-like, gelatinous, amorphous substances. Strictly speaking, colloids represent suspensions of matter in an extremely fine state of subdivision, the suspended particles having diameters varying from 1 μ to 100 $\mu\mu$. The properties of colloids are primarily surface properties. The extent of surface development, and hence the magnification of specific properties, such as solubility, adsorption power, etc., may be seen from the following illustration: A centimeter cube of any solid substance, say platinum, exposes a surface of 6 square centimeters. Let this cube be divided successively and decimally to the dimensions of colloid particles. The total surface then exposed by the platinum will vary between 60 and 6,000 square meters.

Some colloidal properties involved in this problem.—Since colloids play an important rôle in the formation of soil strata and since they

impart to these strata many of their most important properties, it will be necessary to mention in detail some of the more important colloid properties and phenomena.

Colloids are divided into two general classes, namely, suspensoids and emulsoids. Briefly stated, suspensoids are suspensions of solid particles, chiefly inorganic, in a fluid medium; emulsoids are suspensions of fluid or semi-fluid particles. The emulsoids found in the soil are chiefly of organic origin, resulting from the secretions of animals, the exudations of plant roots, the humus, and other products of decaying organic matter brought about through the assistance of bacteria and fungi.

Colloids are also classified as reversible and irreversible. Most of the suspension colloids when desiccated, sometimes when frozen, or when in the presence of electrolytes, coagulate into a solid or semi-solid water-insoluble precipitate. When this solid is placed in water it does not again pass into suspension. It is therefore said to be irreversible. To this class belong the hydrated ferric oxide, the gelatinous silicic acid, the gelatinous, hydrated aluminum silicates, the clays, kaolin, etc. In rare cases one may find aluminum hydroxide.[1]

Suspended colloid particles are either positively or negatively charged. Thus silicic acid, kaolin, and clay particles are negative; the basic hydrated ferric oxide is positive. These charged particles are precipitated by electrolytes, and it has been found that the precipitating power of the electrolyte is specifically a property of the ion bearing a charge opposite in sign to that of the particle. Further, the precipitating effect is greatest for those ions carrying the greatest number of charges.

Factors determining the stability of colloidal clay suspensions.—The effective properties of any colloid suspension depend upon its stability—its power to exist in the colloidally suspended state. The stability is also one factor in the slow transportation of the colloid particles through the soil capillaries. This stability depends not only upon the absence of precipitating ions but also upon the potential difference between the charged particles and the oppo-

[1] Cameron and Bell, "The Mineral Constituents of Soil Solution," *U.S. Dept. of Agric., Bull. 30* (1905), p. 22.

sitely charged solvent. The stability is greatest when this potential difference is greatest; its instability, or its tendency to coagulate, is greatest when this difference approaches zero.

Electrolytic coagulation or precipitation is preceded by the electrical adsorption of ions by the oppositely charged colloid particles. The precipitate carries with it the adsorbed ion or its salt, which in its adsorbed state is more or less difficultly removed by washing. Thus certain salts like those of potassium and ammonium are specifically and tenaciously held by the soil and clays, while the more toxic, less firmly adsorbed sodium salts are leached away.

When present in traces the singly charged H^+ and OH^- ions not only do not coagulate colloidal material but may even increase the stability of similarly charged colloid particles. In the hydrolytic decomposition of the alkaline silicates free OH^- ions are formed. These tend to increase the negative potential, likewise the stability of the negative colloids. Thus in the alkaline-soil solutions silicic acid and the colloidal hydrated silicates are kept to a slight extent, at least, in a state of pseudo-solution. Under the influence of the free carbonic acid and of mineral acids formed by adsorption cleavage of the dissolved salts there may be, as in acid soils, a slight excess of H^+ ions. These stabilize those colloidal "sols" containing positively charged particles. Thus colloidal hydrated ferric oxide is, to a very slight extent at least, rendered capable of transportation by the downward-moving free-water. In the initial stages of the leaching of an original silicate material, where the solution is distinctly alkaline, only the soluble salts and the transportable negative colloidal silicic acid are removed by leaching. Not until the alkalinity has disappeared would it be possible for the positively charged colloidal ferric hydroxide to exist in suspension. Iron in the colloidal form would be, therefore, almost the last colloidal material to undergo leaching.

A soil or clay colloid when once coagulated may again pass into the soluble hydrosol condition.. Numerous experiments have been made dealing with this particular problem. Van Bemmelen has found that when finely divided clay is washed upon a filter the loosely bound coagulating salts are washed away. Upon further

washing, the clay becomes still more finely divided and finally passes through the filter, giving a turbid non-settling suspension. On adding a small amount of an electrolyte the milk-white liquid coagulates and settles. Upon washing again another point is reached at which the particles become infinitely fine and pass through. So it is in clay soils: an excess of water percolating downward removes the excess of coagulating electrolyte from the leached clay. This permits first a swelling of the reversible colloidal material and finally, to a slight extent at least, the gradual re-formation of the colloidal "sol." The suspended particles are thus permitted to pass slowly downward, where they are again coagulated at some lower level.

The inorganic colloids of soils and clays exhibit a marked tendency to adsorb upon their surfaces the various organic emulsoids formed from plant and animal débris. The humus is full of these. The adsorbed emulsoidal material forms an oil-like film about the suspended particles and imparts to them its own reversibility and stability. Hence when a mixture of the emulsoid and suspensoid materials are evaporated to dryness and the dry material is again placed in water the whole mass again passes into colloidal suspension. Furthermore, if emulsoidal material of any sort is added to a coagulated hydrogel, such as clay, the emulsoid possesses the power to peptizate or deflocculate the clay hydrogel, thus rendering it capable of colloidal suspension. By their reversible and protective influence humous materials hinder the coagulation of clay colloids; by their deflocculating influence they tend to make the hard, dry, sun-baked clays again reversible.

The terms humus and humic acid have been mentioned. The latter is a very complex substance of doubtful composition; it is an acid and possesses a colloidal nature. It dissolves in 8,337 parts of water at 6°. Its ammonium and magnesium salts are rather easily soluble; calcium humate dissolves in 3,125 parts of water, while the least soluble ferric humate dissolves in 5,000 parts. The humic acids are solvents for silica. Humic acid has the property[1]

[1] Julien, "On the Geological Action of the Humic Acids," *Proc. Amer. Assoc. Adv. Sci.* (1879), pp. 311–410.

of gluing together vegetable earths into layers impervious to water. Their action consists mainly in the removal of calcium, magnesium, and iron, which are again precipitated at the lower limit of action, either by soluble salts, by exchange of bases, or by loss of water. The precipitated organic humus is finally oxidized and disappears, depositing the base metals as hydroxides or carbonates.

Summary of the mineral constituents of the soil solution.—In summarizing, the mineral matter of the soil solution may be divided into two classes. The more easily diffusible are those comprising the soluble alkali salts, the soluble acid-carbonates of calcium and magnesium, the slightly soluble ferrous compounds, the ferric humates, and the semi-colloidal sodium and potassium silicates. The less easily diffusible are the colloidal gelatinous silicic acid, the gelatinous hydrated silicates, and the colloidal hydrated ferric oxide. The solvent action of the alkaline-soil solution and of the humic acids, aided by the abrasive effects of the earth's displacements, slowly but surely transform the quartz pebbles into colloidal silica. Under the influence of the decaying organic matter the ferric compounds are reduced, temporarily at least, to ferrous compounds. While the existence of ferrous compounds in contact with the oxygenated soil atmosphere must obviously be a short one, the alternate oxidation and reduction permit the slow downward transportation of iron. The decomposition of the original complex aluminum silicates leads ultimately to the formation of the colloidal hydrated aluminum silicates. These are the most complex, most resistant, and the least soluble of all of the decomposition products produced by the disintegration of silicate rocks.

Hence in the leaching of the so-called weathering products of the original glacial till one should expect to find a gradual relative increase in the proportion of the soluble diffusible materials from the surface downward. On the contrary, conditions permitting, a gradual decrease in the proportion of alumina should be observed. This is exactly what is found from a study of the results of the chemical analyses of a complete series of strata in any single complete cut.

The kinds of materials analyzed and the localities from which they were taken.—The kinds of materials analyzed and the localities from which the materials were taken are as follows:

A. Kansan gumbotil, and oxidized and leached Kansan till, from cut on the Chicago, Milwaukee & St. Paul Railway, about one mile east of Foster in the southeast corner of Monroe County, Iowa.

B. Kansan gumbotil, oxidized and leached Kansan till, and oxidized and unleached Kansan till, from cut on the Chicago, Milwaukee & St. Paul Railway, at mile 372, one mile west of Murray, Clarke County, Iowa.

C. Nebraskan gumbotil, Nebraskan oxidized and leached till, and Nebraskan oxidized and unleached till, from cut on the Chicago, Milwaukee & St. Paul Railway, one and one-half miles west of Manning, in the southwest one-quarter of section 18, Warren Township, Carroll County.

D. Illinoian gumbotil, oxidized and leached Illinoian till, and oxidized and unleached Illinoian till from bluff north of Fort Madison, Lee County, Iowa.

The complete sections at each of the foregoing localities have already been given in this paper, but it seems well to bring them together here in relation to a discussion of the chemical analyses of materials:

A. Section in cut on the Chicago, Milwaukee & St. Paul Railway, about one mile east of Foster, in the southeast corner of Monroe County, Iowa:

	Feet	Inches
5. Soil, black, porous	2	
4. Loesslike clay, chocolate-colored, leached	1	6
3. Loesslike clay, light-colored, grayish, on dry surface looks like gumbotil, has chocolate-colored stains, sticky when wet, contains a few small siliceous pebbles, leached	5	6
2. Gumbotil (Kansan), gray-colored, in lower part chocolate-colored; few pebbles; starchlike fracture when wet; leached	12	
1. Glacial till (Kansan), brown in color, with very irregular patches of gray-colored till resembling gumbotil; dry surface of the till is brownish-yellow; damp surface is chocolate-colored; few pebbles; leached to base of cut	5	

B. Section in cut on the Chicago, Milwaukee & St. Paul Railway at mile 372, one mile west of Murray, Clarke County, Iowa:

	Feet
4. Loesslike clay, gray to pale-yellowish color on dry surface with irregular lines of brown; when damp it is grayish with mottling of yellow to brown colors; stands vertically, upper few feet mealy	15
3. Gumbotil (Kansan), gray to drab in color, sticky when wet, hard and tenacious when dry; contains a few siliceous pebbles; leached	11
2. Glacial till (Kansan), oxidized and leached	4
1. Glacial till (Kansan), oxidized and unleached; has many lime concretions	11

C. Section in cut on Chicago, Milwaukee & St. Paul Railway, one and one-half miles west of Manning, in the southwest one-quarter of section 18, Warren Township, Carroll County, Iowa:

	Feet	Inches
6. Loess:		
Leached, yellowish-gray on dry surface; yellowish-brown to buff-brown on damp surface; no shells or concretions	7	
Unleached loess, lighter-colored on dry surface than the leached loess, and when damp it is buff with gray streaks. Contains shells and concretions	5	
5. Glacial till (Kansan), yellow, unleached, with calcareous concretions; numerous pebbles including granites, quartzites, etc. Below the oxidized, unleached till is gray drift with a few pebbles. It is gumbotil-like but effervesces freely. It was probably picked up from the gumbotil zone below	5	
4. Soil band containing carbonaceous material		4
3. Gumbotil (Nebraskan), gray to drab-colored, few pebbles. The upper six feet is fine-grained, gray, and is less sticky and gumbotil-like than the lower seven feet, which is leached, but has some calcareous concretions	13	

	Feet	Inches
2. Glacial till (Nebraskan), oxidized, apparently leached, but has calcareous concretions, upon which are films of manganese dioxide.......	2	
1. Glacial till (Nebraskan), unleached, oxidized, light-yellowish color on dry surface, mottled brownish with gray when damp, many calcareous concretions, expecially in upper ten feet....................................	17	

D. Section in bluff north of Fort Madison, Lee County, Iowa:

	Feet	Inches
4. Loess and loesslike clay, grayish-yellow to buff-yellow............................	7	
3. Gumbotil (Illinoian), drab to dark color; starchlike fracture; few pebbles; leached....	4	6
2. Glacial till (Illinoian), oxidized, leached....	6	
1. Glacial till (Illinoian), oxidized, unleached to base....................................	15	

Chemical analyses of the Nebraskan, Kansan, and Illinoian gumbotils and their substrata.—The analytical data obtained from the chemical analyses of samples taken from localities at "A," "B," "C," "D" have been collected in the following tables. The results are given in two forms, (*a*) the percentage composition with respect to the less mobile constituents, (*b*) the parts by weight of these constituents per 100 parts of the more resistant Al_2O_3.

TABLE I

A. Chemical analyses of Kansan gumbotil and oxidized and leached Kansan till from cut on the Chicago, Milwaukee & St. Paul Railway about one mile east of Foster, in the southeast corner of Monroe County, Iowa.

	a) Percentage Composition				
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO
Gumbotil (Kansan)...........	72.03	4.18	12.27	1.33	2.29
Glacial till, oxidized, leached..	73.11	4.62	11.57	1.66	2.56
	b) Parts per 100 Parts Al_2O_3				
	SiO_2	Fe_2O_3	CaO	MgO	
Gumbotil (Kansan)..........	587.0	34.10	10.84	18.68	
Glacial till, oxidized, leached...	631.9	39.92	14.35	22.18	

TABLE II

B. Chemical analyses of Kansan gumbotil, oxidized and leached Kansan till, and oxidized and unleached Kansan till, from cut on the Chicago, Milwaukee & St. Paul Railway, at mile 372, one mile west of Murray, Clarke County, Iowa.

	a) PERCENTAGE COMPOSITION				
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO
Gumbotil (Kansan)	70.46	4.17	12.04	1.21	0.55
Glacial till, oxidized, leached	71.84	4.62	10.86	1.29	0.72
Glacial till, oxidized, unleached	68.56	4.40	11.13	4.48	0.79
	b) PARTS PER 100 PARTS Al_2O_3				
	SiO_2	Fe_2O_3	CaO	MgO	
Gumbotil (Kansan)	585.2	34.7	10.05	4.57	
Glacial till, oxidized, leached	661.5	42.5	11.87	6.66	
Glacial till, oxidized, unleached	616.0	39.5	40.30	7.16	

TABLE III

C. Chemical analyses of Nebraskan gumbotil, Nebraskan oxidized and leached till, and Nebraskan oxidized and unleached till, from cut on the Chicago, Milwaukee & St. Paul Railway one and one-half miles west of Manning, in the southwest one-quarter of section 18, Warren Township, Carroll County.

	a) PERCENTAGE COMPOSITION				
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO
Gumbotil (Nebraskan)	71.59	4.35	12.79	1.26	0.93
Glacial till, oxidized, leached	66.85	5.92	11.65	3.67	0.78
Glacial till, oxidized, unleached	66.52	4.80	11.18	4.28	1.43
	b) PARTS PER 100 PARTS Al_2O_3				
	SiO_2	Fe_2O_3	CaO	MgO	
Gumbotil (Nebraskan)	559.7	34.0	9.90	7.31	
Glacial till, oxidized, leached	573.8	50.7	31.51	6.71	
Glacial till, oxidized, unleached	594.5	42.9	38.30	12.81	

Table V shows the comparative results of the chemical analyses of "A," "B," "C," "D."

Discussion of the chemical data.—The three localities "A," "B," and "D" show the gumbotil underlying loess or loesslike clay covered by a thin layer of soil. At "C" the Nebraskan gumbotil lies below soil with no intervening loess or loesslike clay. The

TABLE IV

D. Chemical analyses of Illinoian gumbotil, oxidized and leached Illinoian till, oxidized and unleached Illinoian till, from bluff north of Fort Madison, Lee County, Iowa.

	a) Percentage Composition				
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO
Gumbotil (Illinoian)	71.07	4.24	14.91	0.79	0.85
Glacial till, oxidized, leached	72.24	7.43	11.65	0.61	0.95
Glacial till, oxidized, unleached	72.30	3.47	8.59	4.13	1.28
	b) Parts per 100 Parts Al_2O_3				
	SiO_2	Fe_2O_3	CaO	MgO	
Gumbotil (Illinoian)	476.0	28.44	5.34	5.68	
Glacial till, oxidized, leached	620.1	63.80	5.26	8.22	
Glacial till, oxidized, unleached	841.2	40.39	48.10	14.95	

TABLE V

	A	B	C	D
	SiO_2			
Gumbotil	72.03	70.46	71.59	71.07
Glacial till, oxidized, leached	73.11	71.84	66.85	72.24
Glacial till, oxidized, unleached	....	68.56	66.52	72.30
	Fe_2O_3			
Gumbotil	4.18	4.17	4.35	4.24
Glacial till, oxidized, leached	4.62	4.62	5.92	7.43
Glacial till, oxidized, unleached	....	4.40	4.80	3.47
	Al_2O_3			
Gumbotil	12.27	12.04	12.79	14.91
Glacial till, oxidized, leached	11.57	10.86	11.65	11.65
Glacial till, oxidized, unleached	....	11.13	11.18	8.59
	CaO			
Gumbotil	1.33	1.21	1.26	0.79
Glacial till, oxidized, leached	1.66	1.29	3.67	0.61
Glacial till, oxidized, unleached	....	4.48	4.28	4.13
	MgO			
Gumbotil	2.29	0.55	0.93	0.85
Glacial till, oxidized, leached	2.56	0.72	0.78	0.96
Glacial till, oxidized, unleached	....	0.79	1.43	1.28

loess and loesslike clay are of great interest but are not being considered except incidentally in this paper. In places these materials are clearly eolian in origin. In other places the loesslike clay may be related closely in origin to the gumbotil. The presence of loess or loesslike clay above the gumbotil might be expected to have had some slight effect upon the present chemical composition of the gumbotil, and in fact may explain the few percentages in the analyses which might seem to contradict the theory proposed.

It is assumed that the composition of the flour of the unoxidized and unleached till is now the same as it was when laid down by the glacier. The possibility exists, however, that it may have received a small amount of leached material from above, or that it may have lost to the strata above by capillary flow slight quantities of the more easily diffusible dissolved materials. It is not to be expected that its composition will be similar to that of overlying materials which have been subjected to marked chemical changes, to leaching, or to infiltration.

Attention should be called again to the fact that the gumbotils occupy definite topographic positions and that, as a result of erosion subsequent to the formation of the respective gumbotils, the areas of gumbotil are now very limited compared with the extent of the former gumbotil plains.

A study of Tables I to IV will bring out several interesting facts. In all of the series here represented the percentage of Al_2O_3 decreases downward from the gumbotil through the oxidized and leached zone. Except in the case of "B" (Table II), this decrease continues also through the oxidized and unleached zone.

Perhaps the most important evidence in favor of the leaching theory is to be gained from a study of the relative proportions of CaO and MgO in the various horizons. In practically every series the proportions of these two constituents show a pronounced increase downward. Apparent contradictions for both might be considered for MgO in Table III and CaO in Table IV. Field relations will show in these instances either that the gumbotil is overlaid by material containing a higher proportion of these constituents, or that erosion began before the leaching process in the gumbotil was completed. Assuming that the loess or the loesslike

clay is a subsequent formation, it also will have been leached of some of its CaO and MgO. This means a slight increase in the proportions of these two in the stratum below, the leaching of which has not been completed.

The leaching process.—The silica and iron are less diffusible and hence less subject to leaching than are the carbonates of calcium and magnesium, and a much longer time is required for complete leaching. In every instance the proportion of iron in the gumbotil is less than it is in the oxidized and leached stratum just below. Except for the case of the Nebraskan (Table III), the proportion of SiO_2 is greater in the oxidized and leached stratum than in the gumbotil. It should be observed that the Nebraskan at locality "C" underlies the Kansan, and the apparent discrepancy may be accounted for in the transfusion of the alkaline silicates from the Kansan into the upper strata of the Nebraskan below. On the basis of parts per 100 parts of Al_2O_3 not only CaO and MgO but also SiO_2 show distinct evidence of leaching even in the oxidized and leached zone, and this is true for practically every series. On the same basis the evidence points to a leaching of the iron into the oxidized and leached zone from the gumbotil, but the time allowed was not sufficient for the subsequent leaching of the iron from the oxidized and leached zone into the one below. This is not surprising, since, as will be shown later, the iron is the last constituent to be leached away.

The oxygenated and carbonated water falls upon a uniformly level, more or less uniformly constituted, blue to blue-black drift. Percolating downward, it dissolves a portion of the rock material. Hydrolysis follows, and there are liberated successively the hydroxides of sodium or potassium, then of calcium or magnesium, and finally the more or less difficultly soluble hydroxides of ferrous and ferric iron, depending upon the nature of the iron in the original silicate. The ferrous iron throughout the depth penetrated by the dissolved oxygen is immediately oxidized and the deposit assumes the typical iron color of the yellow clays.

The calcium and magnesium hydroxides combine with the carbon dioxide of the soil atmosphere to form the insoluble carbonates. These crystallize out as calcareous concretions. The

soluble alkalies and the alkaline silicates are carried downward by the moving free-water. The negative colloidal silicates and silicic acid are coagulated and thus rendered motionless by the positively charged calcium and magnesium ions. As hydrolysis proceeds the mass of the insoluble material thus formed increases and probably does continue to increase until all of the easily available, hydrolyzable materials are used up or removed.

The second stage of the leaching process now follows. Obviously those insoluble substances which are most easily attacked will be the first to be leached away. These are the carbonates of calcium and magnesium. Although only very slightly soluble, the dissolved portions of these combine with the carbonic acid of the soil solution to form the soluble acid carbonates. These are carried downward to lower levels, where in fissures and crevices they again crystallize as irregular concretions. In this way were formed all of those calcareous concretions which are found in the oxidized zone.

According to the law of mass action, the activity, or the solvent effect, of the carbon dioxide will be greatest at points where its concentration is a maximum. This obviously will be at the upper level of the initially unleached calcareous zone. Owing to its diffusion power some of the carbon dioxide may escape combination at the upper level only to combine at a slightly lower level. Ultimately there will be a lower limit beyond which the carbon dioxide entering from the atmosphere will not penetrate, or its concentration in the soil solution will be too slight to produce any appreciable chemical effect. These two limits of maximum and minimum activity represent the boundaries of the dynamic zone of carbonic acid activity—the oxidized and leached zone. As time goes on the concretions at the upper level disappear, and the levels of maximum and minimum activity move downward simultaneously.

This dynamic zone has played an important rôle in all drift transformations. It spreads horizontally like a continuous sheet of more or less uniform thickness. It is found always directly upon the oxidized and unleached drift and directly below the gumbotil. In the Nebraskan drift it is thin, less than two feet to somewhat more than four feet. The oxidized leached zone of the

Kansan drift averages about five feet, attaining in a few places a thickness of about seven feet. That of the Illinoian has an average thickness not to exceed six feet.

After the leaching of the calcium and magnesium carbonates there follows a third step. When the concentrations of the precipitating calcium and magnesium ions have been reduced below their critical coagulating values new processes occur within the leaching zone. The coagulated iron passes into solution either as colloidal ferric hydroxide by peptization or deflocculation by the emulsoidal organic humous material or through the influence of peptizing ions, or as ferrous compounds by reduction by organic matter. Thus, either by colloidal flow, by alternate reduction and oxidation, or through the medium of its soluble or slightly soluble salts, the iron is leached and slowly passes downward. The silica either in the form of the colloidal gelatinous silicic acid or as the alkaline silicates also moves downward. Likewise, through various peptizing influences the colloidal clays and the simpler colloidal silicates begin to swell and deflocculate. Ultimately some of these pass into suspensions of colloidal particles. They are caught also in the downward current and carried by it to lower levels, where they are again coagulated. Only a very slight amount of this kind of material is leached away. There is left above only the more resistant, less mobile, complex colloidal aluminum silicates.

The stratum now forming, deprived of practically all of its sodium and potassium, of most of its calcium and magnesium, and some of its iron and silica, is the present residuum of the whole chemical leaching process. This is the gumbotil.

Physical and chemical properties of the gumbotils.—The properties of the gumbotil are largely those which one might predict from a knowledge of the colloidal chemistry of clays. Like certain colloids it becomes very hard and tenacious when dry; it swells when wetted and then to some extent passes spontaneously into colloidal suspension. It becomes sticky and sometimes so slippery that under the pressure of the earth above it oozes or slides out of the sides of the hills. It is gray when dry, dark when wet. The characteristic color changes of the gumbotil are those imparted to it

by the colloidal clays, perhaps the kaolin contained in it, the color of the colloidal material being sufficiently strong to mask the reddish-yellow color of any oxidized iron which may be present. This doubtless is responsible for the belief held by some persons that the iron in the gumbotil is deoxidized or reduced, a condition which could hardly be possible in the presence of the oxygenated soil solution.

The chemical analyses of the gumbotils from different drifts and localities show, with respect to certain constituents, a striking similarity. This is especially true for the iron and silica and, as we might expect, for the calcium. Slight fluctuations may be expected due to differences in the nature of the original rock materials, to the amount of rainfall, or to leaching from above. It may be concluded, therefore, that all gumbotils have a common origin—the chemical modification by weathering of glacial till.

Similarities of the gumbotils and the adjacent yellow oxidized and leached zones.—Furthermore, the chemical analyses, as arranged in Table V, show a slightly less striking similarity between the gumbotil and the yellow oxidized-leached clay. Naturally one should expect to find a slightly greater concentration of the diffusible material in the leached zone. One should expect also to find a slight variation in the proportion of any one constituent between the top and the bottom of any single zone. Each level in any one zone is still slightly unleached with respect to another level close to and above it.

The proportions of most of the constituents present in the oxidized-leached and gumbotil zones differ in most of the series by only a few tenths of 1 per cent. When greater deviations occur it can be shown that one or more of the upper strata have been removed before the leaching process was completed. The distinguishing features between these two strata are, therefore, due primarily to differences in the physical properties, and these properties are chiefly the colloidal properties of the clay itself. It is possible that two forms of the same material are being dealt with, namely, the gumbotil, a highly colloidalized form, and the oxidized-leached clay, the non-colloidalized form, that is, a form which in the presence of electrolytes is incapable of assuming

certain colloidal properties. In fact recent uncompleted work by Mr. L. B. Miller[1] gives evidence which not only supports the idea that these two zones differ chiefly in respect to differences in colloidal properties but also strongly confirms the theory that the gumbotil is directly related to the drift. It has already been stated that colloidal properties are primarily properties of the surface. A given colloid material of different degrees of subdivision will adsorb varying amounts of a given substance, and the amounts adsorbed by a given mass of the colloid will be approximately proportional to the specific colloidal surface. Assuming that hygroscopic water adsorbed by clays may be taken as a measure of colloidality and of surface development, Miller has determined the amount of hygroscopic water taken up by each of these clays at 25.° He has found that, beginning with the original drift material the specific surface increases gradually, but at an increasing rate upward to the gumbotil. He has also determined the "total-water capacity," that is, the amount of water per gram which is just sufficient to cause the clays to "run." This likewise is greatest for the gumbotil in any drift, and it decreases gradually downward through the lower layers. The high "total-water capacity" of the gumbotil accounts for the ease with which it slides in exposed cuts.

SUMMARY

The aim of this paper has been to show by field and laboratory evidence that the gumbotils on Nebraskan, Kansan, and Illinoian glacial tills are the result chiefly of chemical weathering of drift. Thus far no distinctive evidence has been found in Iowa to indicate that the bowlder clay from which gumbotil is thought to have been derived differed to any great extent from typical bowlder clay. In the case of the Iowan and Wisconsin glacial tills, which are too young to have had a gumbotil developed on them, the till at and near the surface does not appear to differ in any important respects from the till which is deeper below the surface. In this connection it should be stated that Mr. E. W. Shaw, as a result of his studies of the Illinoian drift in southern Illinois, the Kansan drift in

[1] L. B. Miller, *The Colloidal Properties of Clays.*

northern Missouri, and other till sheets elsewhere, believes that the upper parts of the tills have been, from the times of deposition of the drifts, somewhat different from the middle and lower portions of the drift.[1]

It should be stated that, although it is believed that gumbotil is essentially the result of chemical weathering of glacial till, it is recognized that wind action, freezing and thawing, burrowing of animals, slope wash, and other factors may have contributed to the formation of these gumbotils.

In a subsequent paper attention will be directed to the fact that the gumbotils, on account of their distinctive characters, wide distribution, and topographic positions, are the most satisfactory criteria that have yet been found for differentiating the older drifts. Furthermore, since the gumbotils are the result of changes which took place in interglacial times, they may be considered in relation to the problem of the relative durations of the interglacial epochs.

The gumbotils strengthen the view now generally accepted that the history of the Glacial Period involves, not a few thousand years but probably hundreds of thousands, and possibly millions, of years.

[1] E. W. Shaw, "Characteristics of the Upper Part of the Till of Southern Illinois and Elsewhere," *Abstract, Bull. Geol. Soc. Amer.*, Vol. XXIX (1918), p. 76.

DIASTROPHISM AND THE FORMATIVE PROCESSES

XI. SELECTIVE SEGREGATION OF MATERIAL IN THE FORMATION OF THE EARTH AND ITS NEIGHBORS

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In the last number of this *Journal*[1] I endeavored to deduce from a comparison of the earth with Mars, Venus, and the moon, the order of magnitude of the total shrinkage suffered by the earth. The results proved surprisingly large. Not only that but they seemed to show that the shrinkage per unit of mass-increase became greater as the total mass grew. Since small bodies have but feeble gravitative ability to gather and hold the lighter order of molecules in a free state, it seemed probable that the moon and Mars contain higher proportion of the heavy molecules than Venus and the earth. This seemed to add emphasis to the high densities of Venus and the earth compared with the moon and Mars. It appeared to strengthen the presumption that, in this group of bodies at least, the degree of density was due to the concentrating effect of superior mass rather than original heaviness of material.

However, final conclusions were held in abeyance until the modes of organization of the four bodies could be studied with a view to detecting the probable laws of their segregation in so far as these affect the proportions of inherently light and inherently heavy materials. It is this inquiry that forms the theme of the present paper.

The subject necessarily reaches back to the genesis of this group of bodies, and the discussion will need to concern itself quite as much with the dynamic environment that influenced their formation as with the material that entered into it. The

[1] "The Order of Magnitude of the Shrinkage of the Earth Deduced from a Comparison with Mars, Venus, and the Moon," *Jour. of Geol.*, XXVIII (1920), pp. 1–17

study need not, however, go much beyond the conditions that determined the amount and nature of the material, the mode of aggregation, and its physical state. It must be specific enough, however, to touch the conditions that controlled the relative proportions of inherently heavy and inherently light material. It is therefore necessary to consider with some care the basic laws of organization of such bodies so far as these bear on selective segregation. It will save time and help toward clear treatment to give at the outset what seem to me to be the more essential principles that control the formation of cosmic bodies. It will not be amiss if these are made rather sweeping, provided they are definite enough to apply to the particulars required by our problem.

PRELIMINARY CONSIDERATIONS

While the four bodies named will usually be in mind when other bodies are not specified, there will be occasion to use certain terms in other than their commonest senses, and so let us agree upon these at the outset. By cosmic units let us understand, not simply celestial bodies, but organized bodies of any kind, whether large or small, whether "organic" or "inorganic," provided they serve a unitary function in natural processes. Let us recognize that these range from the atom, whose organization is now being pursued with a skill and success worthy of the highest admiration, up through the molecule, the crystal, the chondrus, the colloidal unit, the cell, the biologic organism, the planet, the star, the star cluster, to the stellar galaxy, at least. Let these more salient types stand for the multitude of intermediary and divergent species of divers sorts that make up the full series. Let them also stand for the unknown extensions of the series downward and upward. Let us agree that the only essential of a cosmic unit is an individualized organization which has its own material center and its own dynamic province. These organized units of course enter into varied relations with one another and form a great complex super-series, but let us consider merely the features that are common to all because essential to all. Among these essentials should appear, in their true relations, those particular features we need to apply to the solution of our special problem.

The wide range of the category thus recognized implies that the study of the organization of cosmic units is not a theme which falls solely within the province of any one of the natural sciences as we now know them; it is common ground, belonging to each and all in so far as their problems reached back into it. The biologic student of the genesis and career of the iron bacteria may invade, of his own right and to any extent that serves his purpose, the Proterozoic terranes or any other terrestrial field that promises him evidence, and we of the geological school may not say him nay, however much we may claim the province as peculiarly our own in respect to our own problems. Each particular science is best suited to make certain inquiries into the origin of organisms and of organizations, and to yield certain contributions to the common science of cosmology, using the term in its broadest sense as the science of cosmic organization, in distinction from cosmogony, which in its original sense—the birth of the cosmos—belongs to philosophy, theology, and mythology.

The cosmic systems mount up by hierarchies from what seem simpler to what seem more complex, but in ultimate analysis all, even the atom, and perhaps even the electron, are themselves complex, and the depth of such complexity is at present unfathomable. This pervasive complexity puts all in a common class and, in some sense, simplifies the common cosmologic problem, for its essence lies in finding those principles of organization that are so far essential to any organization as to be common to all.

FUNDAMENTALS OF COSMIC ORGANIZATION

I. Every cosmic unit bears a dual aspect, a material organization, and a dynamic organization. In ultimate analysis these may be merely different phases of the same fundamental entity, whatever that may be, but in their sensible aspects they are distinctly diverse. The one is very tangible and impressive and has almost monopolized attention; the other is invisible in itself and has fallen much short of the recognition it deserves as an essential element in every cosmic organization. The first is too familiar to need emphasis here; the second requires all the emphasis which a neglected essential can well receive.

II. The material factor of every cosmic unit is not only pervaded internally but is surrounded by a field of force, dominantly attractive but partially repellant. In the present study, the sphere of dominating attraction—the sphere of gravitative control—will, for brevity, usually be spoken of as though it alone represented the dynamic element of the dual organization, for it is chiefly the outlying field of gravitative control that functions actively in the selective segregation of material in the formation of cosmic bodies.

The extreme theoretical reach of gravitation is indefinite, but within a certain portion of this indefinite field, the attractive force of the particular body under study is sufficient to give it immediate control over bodies inferior to itself, unless they carry kinetic energy of their own in sufficient amount, and properly directed, to insure their escape. This field of superior force constitutes the body's sphere of control.[1] It is necessary to note that this control is merely *immediate* control; there are usually, perhaps always, higher types of control which hold ulterior sway over these, but this superior sway is exercised in such a concurrent way as not to prevent the immediate control essential to the minor body as a condition of its own existence and perpetuity. These higher controls may spring from some single more massive body or from some composite organization, as a star group. The superior spheres of control envelop the minor spheres of control; thus the moon's sphere of control revolves within that of the earth; the earth's sphere of control revolves within that of the sun; the sun's sphere of control revolves within the sphere of control of the "local cluster" of stars, and this in turn within the sphere of

[1] The recognition that cosmic bodies are surrounded by spheres of gravitative control is not at all new but merely neglected; Laplace worked out "the spheres of activity" of the planets—here called spheres of control to avoid confusion with the indefinite outward extension of the influence of the cosmic body. The spheres of control of the planets have been worked out more recently on a different basis by Moulton (*Popular Astronomy*, No. 60, May 15, 1899). The spheres of equal attraction, a different matter, have been worked out by the senior Asaph Hall (*Popular Astronomy*, April, 1899). The concept of a sphere of control is herein given a wider application than is common, and is assigned an essential function in the organization and maintenance of cosmic bodies. The concept is regarded as a helpful means of research, particularly as an aid to visualization.

control of the stellar galaxy. The sphere of control of the atom enters into the sphere of control of the molecule, and that into higher orders in succession up to the earth and beyond. The whole cosmic scheme seems to be a system of such hierarchies whose limits in either direction are unknown.

III. The dynamic value of each sphere of control dies rapidly away from the mass in which it centers to its outer border. Not only this, but each sphere of control that revolves within a superior sphere of control is larger or smaller, more effective or less effective, according to its position within such superior sphere of control. It is likely to be either increasing or diminishing as the body in which it centers swings through its orbit. If it were made to constantly approach the controlling body, its extent and efficiency of control would grade entirely away to extinction before such superior mass was reached.

IV. In such spheres of control as center in single great masses, the differential pull of the controlling mass becomes so great relatively, in its innermost portion, that bodies of a minor order intruding upon it are liable to be disrupted. When the approaching minor bodies are gaseous, their spontaneous tendency to dispersion insures their dissipation. When they are solid, the degree of fragmentation to which they are subject is likely to be limited to certain sizes, for as the fragments grow small the strength of their cohesion increases relative to their mass. Cohesion is not likely to be important in large bodies because they are usually self-compressed and hot within to such a degree that their tendencies to expand, when pressure is relieved, usually surpass their coherence.

The outer border of the disruptive zone is known as the Roche limit. Its determination by Roche was based on an ideal homogeneous fluid satellite approaching an ideal homogeneous fluid planet of equal uniform density, cohesion being neglected. He fixed the limit of disruption at 2.44 times the radius of the planet.[1] This limit is in close accordance with what seems to be the realized result in the case of Saturn's rings which stand as the classic example of minute division and distribution in response to this disruptive effect. The mathematical conclusions of Roche were amply

[1] Edward Roche, *Memoirs de l'Académie Montpelier*, I, p. 243.

supported some years later by the studies of Clerk-Maxwell,[1] and their common results were afterward verified by the spectroscopic observations of Keeler, who demonstrated that the rings are formed not of gas, as once supposed, but of discrete particles revolving in independent orbits, in other words are minute satellites or satellitesimals. From a recent study of the albedo of the rings, Bell has concluded that the largest masses in them probably do not exceed three meters in diameter—at least they are not more than a few meters across—while the majority of the visible particles are very much smaller, ranging down to the dimensions of wavelengths of light.[2]

For the immediate purposes of our study, the important point is not so much that bodies entering this zone of disruption either from without or within are reduced to relatively small particles, though this is important, as that these conditions of stress from the controlling body stand in the way of the organization of any new body within this zone. So far as the aggregation of independent bodies of any notable mass is concerned, this is an inhibitive zone. Considered with reference to the controlling body, it may perhaps be said to be a protective zone, tending to preserve its isolation, independence, and undivided sovereignty.

In view of uncertainties as to the precise qualifications the Roche limit might require in the case of a rotating nebular spheroid, Moulton worked out a limit of similar nature but on a different basis, the purpose of which was merely to fix a more certain limit within which the organization of nebulous matter would be inhibited.[3] This limit was placed at 1.38 times the radius of the nebular spheroid, or a little more than half the radial extent of the Roche limit.

V. Accepting as a working basis the Newtonian doctrine of the unlimited penetration of the force of gravitation, it is a logical deduction that all space is under the immediate domination of

[1] "On the Stability of Motion of Saturn's Rings," *Scientific Papers of James Clerk-Maxwell*, Vol. I, pp. 288–375.

[2] Louis Bell, "The Physical Interpretation of Albedo, II. Saturn's Rings," *Astrophysical Journal*, L (July, 1919), pp. 1–22.

[3] F. R. Moulton, "An Attempt to Test the Nebular Hypothesis by an Appeal to the Laws of Dynamics," *Astrophys. Jour.*, XI (1900), pp. 122–26.

some dynamic organization or some combination of such organizations, except perhaps that theoretical neutrality may arise momentarily on the border lines of spheres of control where exact balancings of attraction may obtain for an instant; but as all celestial bodies are moving relative to one another this can only be transient and unimportant. The concept of such pervasiveness of stress throughout all cosmic space has the merit of dismissing from serious consideration certain inherited notions, for example, that somewhere in space there may be regions where "primordial" matter may have lurked in idleness from a supposed beginning, or where nebulous matter, or dissipated particles of any sort, may somehow assemble purely under their own attraction and later drift into the active cosmic world as quasi-primordial matter, and similar notions that seem to be but reshaped vestiges of oriental concepts of primitive chaos. A much more important function of the deduction, however, is its amplification of the doctrine of dynamic encounter.

VI. From the preceding generalizations it follows that the spheres of control of cosmic bodies are either perpetually plowing through the higher orders of spheres of control that envelop them, or are impinging upon other spheres of control of their own type. In either case, their own domains, as well as those of the bodies with which they interact, are perpetually suffering encroachments. Innumerable dynamic encounters of widely varying types and moment thus spring from cosmic movements. As an incident of these innumerable encroachments of one domain upon another, transfers of the minuter class of units from the field of dominance of one controlling center to that of another are almost perpetual occurrences. They constitute a system of exchange of the first order of extent and seem to be a vital factor in cosmic life. In the case of the earth, revolving in the sphere of control of the sun, this system of exchange is regarded as having a very high order of importance in the maintenance of our atmosphere and the increase of our hydrosphere.

Since encounters of some order of importance are almost infinitely frequent, it is necessary to specify explicitly the nature of the encounter in any argument that is based on frequency of

encounter. Furthermore, in determining the frequency of a given class of encounters, it is not sufficient to postulate an artificial case convenient for computation, for actual cases usually involve a natural selective adjustment of associated bodies with reference to one another. And further, the present deployment of stars may not be identical with that of earlier ages. And still further, if the frequency has for its criterion a given effect or is to be considered with reference to a given effect—explosive action for example—susceptibility to such effect is as important as the nature of the encounter. These requirements are commonly neglected.

VII. All cosmic organizations seem to be the products of opposing elements. The balance between these opposing factors seems to form the critical issue on which their endurance depends. These opposing factors vary with age, state of growth, environment, and other conditions. Out of these variations of balance arise stages of increase and depletion, of partial or total disorganization and regeneration. The history of the cosmos seems to be essentially a succession of cycles arising from either internal or external disturbances of balance. Interestingly enough, the atom happens just now to afford one of the best illustrations of internal disturbance leading to transition in organization. Thought until recently to be beyond the utmost resources of disintegration, it is now known that some of the heaviest atoms are undergoing "spontaneous" disorganization. By way of offset for the old error, as it were, the dictum now is that no known device, appliance, or force can stop this disintegration. Future inquiries will probably disclose the golden mean between these extremes. In spite of all disintegrating influences, the integrity of atomic organization, in the main, is maintained to an extraordinary degree. In the larger cosmic world there are intimations of analogous "spontaneous" disintegrations standing over against similar persistency. The eruptivity of the sun, on which the planetesimal hypothesis is founded, is revealing striking analogies to the partially disintegrating atom as will be detailed later. Some of the great hot stars give intimations of a very delicate balance of internal forces. Over against the enormous concentrating force of gravity and its allies, stands the scarcely less potent alliance of the forces of dispersion. These

latter seem, on the whole, to be overmatched by their opponents, as implied by the very existence of the stars; and yet the forces of dispersion are clearly successful in particular ways, as, for example, in the matter of radiations and in some loss of high-speed molecules and of electrons.

In this state of wavering balance between internal contending forces, those great seething bodies are plunging at high velocities through what, in a material sense, is an approximate vacuum, but what, in a dynamic sense, is an approximate plenum, a plexus of lines of force of almost infinite complexity. They are thus speeding through a perpetual succession of contingencies of external disturbance. Their hold upon their own material hangs on the perpetuated superiority of their concentrative forces, expressed typically but not wholly in their spheres of gravitative control over their dispersive forces. If the controlling spheres are invaded in a shallow way there is likely to be only trivial loss; if they are invaded deeply, serious disintegration is the logical effect. It is important to note that this disintegration is a joint effect, as much due to the approximate balance of the internal forces as to the disturbing power of the external forces.

And so in dealing with phenomena of this class, it is not more important to inquire into the direct action of the external agencies than into the state of balance of the powerful forces within these supremely active organizations themselves. This is the more imperative because there is growing reason to believe that certain orders of stars are at or near the limit where growth in mass is overmatched by concurrent growth in dispersive forces. If this belief is well founded, such nearly balanced giants of the skies may be regarded as peculiarly susceptible to disturbances of equilibrium arising from the intrusion of foreign dynamic influences into their domain, or perhaps equally their own penetration into areas of concentrated stress arising from special marshallings of other great bodies.

These considerations are deployed at some length here because the stellar conditions that render dynamic encounter effective are too commonly overlooked, and because these conditions are vital in considering cosmic disorganization which in turn is regarded as a step necessarily precedent to cosmic reorganization.

VIII. There is pressing need for rectified concepts of cosmic time and stellar endurance. The recent deep penetration of the stellar field by improved instruments, increased skill, and new methods has forced a revolutionary enlargement of concepts of interstellar space, while co-ordinate enlargements of concepts of cosmic time have not kept apace. And yet time and space are necessary correlatives in stellar movements and in stellar organization. Time concepts must keep pace with space concepts if consistent views of organizing processes are to be entertained. Inadequate concepts of time retained from old estimates of the sun's longevity and like sources now embarrass the free acceptance of cosmic views—if these imply great intervals of time—much as they restrained geological interpretations during the last century. It may be wholesome therefore to inquire specifically: What length of life is implicitly assigned to stars when they are made integers in the evolution of a globular cluster or of a galaxy? What intergenetic periods mark off the generations of stars? What careers appropriately fit them into the vast cosmos that is now revealing itself? And then, subordinate perhaps to the life of a star, what intergenetic periods mark off the generations of planets?

It is to be recognized, of course, that the career of a planet may belong to a different order of magnitude from the career of a star, or of a star cluster, or of the galactic system, and no doubt these differ among themselves. And so our immediate problem may not be more than remotely concerned with these immense questions, but yet it is related to them, and its answer should be consistent with them. Perhaps all that need be said here is that when the estimates of the longevity of stars, star clusters, and the stellar galaxy are brought into harmony with the time requirements of their own processes of organization and their own normal careers, students of the evolution of our little planet will probably feel quite as much call to amplify as to repress their interpretations of the terrestrial time factors in order to bring them into harmony with those of the higher systems.

IX. As a matter of scientific conservatism, it should be taken for granted that the sole source of material and of energy for the formation of new organizations is to be sought in the dissolution

of pre-existent organizations. In most cases, if not in all, however, the dissolution of such previous organizations is not ulterior dissolution; it is usually only the disintegration of one order of organization into elements of a somewhat lower order. Neither dissolution into chaos, in any strict sense, or into ultimate factors, nor generation from chaos or from ultimate factors or from anything that is absolutely new, seems to have any naturalistic warrant so far as present cosmic processes are concerned. Nor is there much more warrant for bringing into play any really unknown force or agency, though the discovery of new ways of action of known forces and agencies is to be expected. Scientific inquiry in genetic lines appears therefore to have for its appropriate field of study little else than partial disorganization followed by corresponding reorganization, though not necessarily of the same type, order, or extent. The scientific student therefore hesitates to call into service any material or energy which he cannot trace back to some known source.

X. In the formation of new cosmic bodies, even of the "inorganic" class, an organizing germ or nucleus, inherited from some parent organization, seems to have much the same function, and to be about as necessary as the seed or the ovum of an organism of the "organic" type. In either case the germ must apparently have both a material and a dynamic factor. This necessity appears to be chiefly due to the essential part which a collecting field of force and a retaining sphere of control play in organizing a cosmic body. In the concrete discussion to which we shall now turn, the strength and the reach of the organizing field of force will be held to be the chief criterion that determines whether dissevered or disorganized masses of matter shall reorganize as single bodies and pursue independent careers, or shall continue to be merely scattered food to be picked up by bodies already organized and endowed with effective collecting fields of force.

THE SELECTIVE SEGREGATION OF PLANETARY MATERIAL

In this discussion there will be no occasion to consider any hypothesis of the origin of the four bodies under study that has not been worked out into such definite terms as to bear specifically

on the question of the segregation of inherently heavy from inherently light material, the crux of our problem. Two postulated origins may clearly have such bearings, both of which are now familiar: (1) derivation from a rotating nebular spheroid by centrifugal separation brought into effective action by cooling and consequent acceleration of rotation, and (2) derivation from solar material ejected either spontaneously or under the stimulus of a passing body. The principles involved in these two types will probably serve to cover any other origin for which good reasons may be assigned.

While I am unable to see how planets such as form our system can have arisen from a rotating spheroidal nebula by centrifugal action, it yet seems best, out of deference to any who may still think that some view of this general type is tenable, to discuss this postulated mode of genesis in so far as it bears on our problem. It will only be necessary, however, to review the phase of the theory most dependent on the dynamic environment which controlled the evolution, for that touches the soul of the subject.

THE CENTRIFUGAL EVOLUTION OF A GASEOUS SPHEROID UNDER ITS OWN DYNAMIC ENVIRONMENT

Every organized nebula, like every other organized body, must have an adequate enveloping field of force and sphere of control as a necessity of its organized existence (I and II, above). The postulate that there was once a spheroidal nebula of the mass of the solar system which in contracting shed secondaries at various distances from its center as far out as $2\frac{1}{2}$ billion miles and yet was able to hold them then and afterward, carries the implicit assumption that it had a distinctly effective sphere of control. The shedding of the four little bodies under study took place only after the postulated nebula had shrunk to about one-twentieth of the radius it had when it displayed its effective holding power by its control over the material shed for the planet Neptune, while the outermost reach of its holding power must have extended much beyond this. At the relatively concentrated stage when the shedding of the substance for our little group of bodies took place, the inner zone of control must have grown relatively intense; the

disruptive belt just outside the rim of the rotating spheroid (IV above) must have had a notable development. If it were quite safe to assign it the full breadth of the Roche limit, which holds so well in the case of Saturn's rings, it would have had, taking the earth stage as a mean, an outward reach of 133,000,000 miles. But let us follow the safer course of using the conservative criterion of Moulton which gives a zone of 35,000,000 miles (IV above). Let it be recalled that the fragments of a disrupted mass revolving about the controlling body under the conditions of this case take orbital courses more or less parallel with one another. If the gaseous rim of the nebula could have been "thrown off" as a coherent body, it would not only have been disrupted into minute constituents, but these would have been given orbits of a type much like those pursued by the particles in Saturn's rings, all the more because the constituents of a gas tend to disperse themselves by their own interaction. This is equivalent to saying that the dynamic conditions within this zone were such as to inhibit any aggregation of this material into a common large body like the earth, Mars, or Venus, or into a lesser number of bodies of any considerable size. Even when such scattered orbital matter was left by the withdrawal of the nebula in the less intense horizons of the nebular field of force, its aggregation would still be greatly embarrassed by the superior control of the central mass. It is a common error to think of such scattered matter as though it were in neutral space entirely free from all forces except its own mutual attractions. The control of the central body so far embarrasses the assemblage of minute particles under the actual conditions of such a case as this as to render their aggregation into a single body improbable, as Moulton has so effectually shown.[1]

However, for the sake of seeing its bearings on the problem in hand, let us waive this improbability and try to follow the aggregation of the minute constituents of a quasi-Saturnian ring "thrown off" from the postulated rotating nebula.[2]

[1] F. R. Moulton, "An Attempt to Test the Nebular Hypothesis by an Appeal to the Laws of Dynamics," *Astrophys. Jour.*, XI (1900), p. 115.

[2] The deduction that the molecules shed by centrifugal action from a rotating gaseous spheroid would pass into individual orbits and form a planetesimal system does not depend solely on the Roche effect, as shown in "The Bearing of Molecular Activity on the Spontaneous Fission of Gaseous Spheroids," Publication No. 107, Carnegie Institution of Washington, 1909, pp. 161–67.

Let it be noted at the outset that the material to be aggregated was planetesimal in a very strict sense of that term. Each integer, whether it be a molecule, a particle, or any such more considerable aggregate as might be formed under the conditions of the case, was pursuing a nearly circular orbit around the central controlling body, the nebula at first, the sun later. This precisely fits the definition of a planetesimal. This means that the particles were in a dynamic, not a static state; they were under control, not free. Whatever aggregation followed was therefore of the planetesimal type, that is, particle joined particle in an individual way as their orbits and orbital forces permitted. Their orbital velocities hovered about that of the earth (18.6 miles per second) let us say, as a mean, the inner faster, the outer slower, the orbits of those equally distant from the center slightly inclined toward one another. Beside these differences of velocity and inclination—that arose from the nature of the case—the planetesimals inherited diverging courses from mutual collisions and rebounds as they emerged from the gaseous into the orbital state. To overcome these divergencies of orbit and these differences of speed and develop aggregates of one kind or another in place of the molecules inherited from the gaseous state, there were two classes of forces: (1) the collective attraction of the whole ring or disk or some bunched portion of it, and (2) the aggregating influences of individual molecules upon one another. The first would tend to make a single planet, if the whole were drawn together, or a few planetoids, if there was aggregation by bunching; the second would make at first a multitude of minute particles which would grow to larger sizes in proportion as the agencies of later aggregation proved superior to the effects of fragmentation, exfoliation, trituration, and friction in other forms after the particles had grown large enough to give these notable efficiency. Only the salient features can be touched here.

1. The ground of the first class of agencies has already been covered. No general nucleus nor any effective bunching was inherited from the nebula; indeed concentration was definitely inhibited up to the time of the withdrawal of the Roche limit. There might be, to be sure, a certain kind of transient bunching of the planetesimals in their orbits, such as affects the present planets,

but the relative rates of revolution that brought this about would destroy it. Collectively, the planetesimals would be so distributed that they would have almost no concentrating force of their own that was not later reversed or neutralized by their own orbital motions.

2. Practically the whole aggregation, then, would be that of the formation of discrete particles such as started with the joining of molecules and were built up thence into crystals, pellets, nodules, or whatever these might grow into later. The chemical combination of molecules would take place at proper temperatures readily enough by simple contact, whether this arose from collision while in the state of a gas, or from contacts brought about by planetesimal motion, or otherwise. Such refractory chemical compounds as now form the main mass of the solid bodies of the moon, Mars, Venus, and the earth, would probably be formed at high temperatures while they were still a part of the postulated nebula. The critical feature of the case lies in the way these complex refractory molecules would be gathered together after they were formed. While they remained in a free state as molecules they would normally tend to rebound on collision as molecules do and so maintain their free state. Even if they were brought together under conditions favorable to remaining together, their rotations or vibrations would tend to throw them apart, as would also subsequent collisions. To overcome these adverse influences, there was need for some special uniting agency, as is well recognized in the familiar case of the formation of the globules of fogs and clouds from water vapor in the atmosphere. It was long supposed that there must be a dust particle or some similar aggregate to serve as a collecting center (the "seed," X, above); but it was later found that molecules electrically charged serve this function also. In our problem, the formation of the first minute aggregates is the very crux of the question, and we cannot assume the existence of any such dustlike aggregates as the means of starting the process. But molecules electrically charged would probably be freely developed by friction, by the action of ultra-violet light, and by other means, and such charged molecules might well serve as the "seed" for starting the minute aggregates.

How far would such aggregation be likely to go, as a rule? There is no need to consider exceptional possibilities, for our problem relates to the common average result. The attraction between two molecules oppositely charged is many billion times greater than their gravitative attraction[1] and may be large compared with the inertia of their relative motion. Charged molecules might then serve as very efficient centers for the gathering-in of molecules, as also very small particles. But an electric charge is confined to the surface of a particle, which increases as the square of its radius, while gravitation varies as the mass which increases as the cube of the radius. And so, after a certain amount of growth, the charges carried on the particles would have less attractive power than the masses into which the particles had grown. But a more important practical consideration lies in the fact that electric charges of like kind repel one another and thus limit the total charge likely to be gathered on a given mass under natural conditions; for example, any electric charges which a forty-pound bolide would probably pick up naturally would lend little aid in gathering in other forty-pound bolides to form a forty-ton bolide. There is thus an obvious limitation to the range of effective electric aggregation, however efficient it may be as an originating agency. A beautiful illustration at once of such effective aggregation and of its limitation is presented by the formation of snow crystals from vapor in the air. These form and grow with great facility up to a certain size when the temperature of moist air falls below the freezing-point; but after a certain moderate growth, the limiting and adverse conditions increase in relative efficiency and arrest further growth; not infrequently it is reversed.

In the case of cosmic particles probably the most effective preventive of indefinite growth is the friction and collision of the masses, themselves. As the particles grow into nodules of notable size and mass, their cohesion is less effective relative to their moving force, and they more readily go to pieces on impact. Trituration and other lesser effects of moving contact would be more frequent

[1] R. A. Millikan, in a personal communication, states: "The attraction of two opposite electric charges is 10^{27} times as great as the gravitative attraction of two atoms of hydrogen."

and perhaps more effective on the whole than fragmentation. This would quite surely be true of the minute particles. According to the interpretation of Bell,[1] a milling process of this triturative sort has proved very effective in reducing to minute sizes the satellitesimals of the Saturnian rings. When masses of any considerable size were reached, probably exfoliation from the effects of rotation in the unscreened rays of the sun would give rise to flaking and thus prepare new matter for the milling process.

On the other hand, if magnetic particles were much developed, it is probable that their special attraction would aid in building up masses, so far as the supply of such material went. Probably such malleable substances as iron, nickel, and the other metals would weld rather freely by impact. Metallic particles might thus unite nearly to the extent they were permitted to come into collision. Such stony substances as brought crystalline or concretionary forces into play would probably build up more readily than other matter and more effectively resist destructive agencies afterward. But it must be noted in all these cases that as the molecules were more or less heterogeneously mixed originally, the opportunities for assembling homogeneous matter to form aggregates of any one kind would have natural limitations.

The logic of the case, taken all together, seems to lead to the conclusion that aggregates arising under these ideal planetesimal conditions would be limited to small sizes as a general rule. This is in harmony with the results realized in the Saturnian rings, and also in the zodiacal planetesimals to be more fully discussed in the next article. It is also in harmony with the dimensions attained by the chondri and chondrules that form characteristic constituents of 90 per cent of the stony meteorites. These range in size from a walnut down to spherules of dustlike minuteness.[2]

The point of most critical importance to our inquiry is the effect on selective action introduced by these growths so far as they went. In the first place, all such matter as continued in a free molecular state, whether aggregated as gases or deployed as planetesimals, would not be gathered about these small aggregates

[1] *Loc. cit.*

[2] O. C. Farrington, *Meteorites* (1915), p. 102.

by their own gravitative power. Incidentally molecules might be entrapped or occluded within these small bodies, or chemically united with them, or possibly even held against them by surface adhesion; but, otherwise, free molecules would rebound and escape control. Those solid particles that were highly elastic would also largely escape by rebound; those that were inelastic would more largely remain adherent after impact. Malleable substances like the metals would be likely to weld and cohere by collision. In general, these cohering bodies belong to the heavier order of substances, and so bodies formed in this way would be for the greater part selectively heavy.

If we could be sure that the chondrules of meteorites represent accretion of the foregoing type—a hypothesis to be seriously considered—it would give a specific insight into the cosmic aggregates of this order, for then they might be said to be dominantly formed of ferro-magnesian silicates, nickel-iron, and metallic sulphides, but it would be premature to draw this conclusion.

At any rate, since, on the one hand, these small bodies could not hold free molecules of the lighter order, and, on the other hand, the conditions were favorable for the aggregation of metallic substances, heavy silicates, sulphides, and so forth, it seems safe to conclude that *these small aggregates contained a relatively high proportion of inherently heavy matter.*

It seems to follow then that, if Mars, Venus, the earth, and the moon could have been gradually built up by the assemblage of particles, crystals, pellets, nodules, or even more considerable masses formed in this selective way, the percentage of heavier constituents could scarcely have been less in the earlier stages and in the smaller bodies than in the later stages and in the larger bodies, while they were probably somewhat distinctly greater; for in so far as these bodies succeeded in becoming large, they could then, but only then, have held the lighter order of molecules in a free state and thus have reduced their mean density. When atmospheres and hydrospheres were thus added, the processes of oxidation, hydration, and carbonation became important and the groundwork was laid for petrological derivatives from the products of these processes. A large class of the rocks and minerals of the outer

part of the earth, which usually have rather low specific gravities, are probably wholly dependent on the presence of the atmosphere and hydrosphere at the time of their formation. And so, if the moon, Mars, Venus, and the earth, could have been built up in this way, the moon should have the highest percentage of heavy material and the others should follow in the order of their masses, atmospheres, and hydrospheres. But it was previously shown that the conditions were very adverse to the building up of these four bodies in this way and there is no likelihood that they had such an origin.

It is perhaps worth while to add that, even if we were wrong in concluding that the planetesimal aggregates would be small, the result would be little different in density or in physical state, for as the aggregation of the particles in their orbits proceeded, the resulting aggregates would become more widely separated and further aggregation would take place only at correspondingly longer intervals. There would be little change in the kind of material or in the heat effects. The material would be a little more bunched before infall, but the bunches would be more scattered in space and successive infalls more distant in time. Precipitate aggregation is quite out of the question under these conditions.

As remarked at the beginning of this section, the material discharge from the rim of a rotating spheroid of gas by centrifugal action should form an ideal system of planetesimals, and so the method of their growth may be taken as a type of such action where the molecules are given subparallel orbits from the start and there is no commanding nucleus to gather them into bodies of the planetary order.

If this analysis is correct, it will be seen that the chance of developing a molten earth from a rotating gaseous nebula by centrifugal separation is about as remote as could well be imagined.

THE SELECTIVE SEGREGATION OF MATERIAL UNDER THE PLANETESIMAL HYPOTHESIS

The particular form of the planetesimal hypothesis which has been most fully worked out and tested postulates that the material of the planets was derived from the sun by means of its own

ejective activity stimulated to special intensity by the differential attraction of some passing body. Two essential factors are involved: (1) the ejection to the requisite distance of the requisite matter—only a fraction of 1 per cent of the sun's mass; and (2) the addition of sufficient transverse momentum to cause the ejected matter to revolve about the sun. The latter is the more critical factor, for the eruptivity of the sun is known to have such a high degree of efficiency, even at the present time, that only a relatively slight increase is required to project the small fraction of the sun's substance to the distance of the planets. Such projections would, however, fall back to the sun, unless they were given a transverse motion by some agency other than radial projection. A passing star or other body has been postulated to meet this requirement. The tidal stresses developed in the sun by such passing body would stimulate eruptivity and give direction to the projections while the pull of the passing body would draw the ejected matter into orbital courses.

In about a half-hundred cases worked out mathematically by Moulton to test the validity of the postulated effects, a star of medium size passing at from one to five astronomical units' distance was taken as the parent of the orbital motion; its diverting competency was found to be unexpectedly effective.[1]

Later it was suggested that a much smaller body—passing however much nearer to the sun—might serve as well to give both the tidal stimulus and the transverse motion required, but this has not yet been worked out mathematically.[2] Still more recent studies have led to the belief that there is a wide range of possibilities respecting the co-operating body, as will be specified later.

RECENT DISCLOSURES BEARING ON THE SOLAR PARENTAGE OF THE PLANETS

Respecting the projectile power of the sun, important light has been shed by very recent discoveries. Remarkable eruptions of the sun took place on May 29 and on July 15, 1919. A fine series of spectroheliographic photographs were taken at the Yerkes

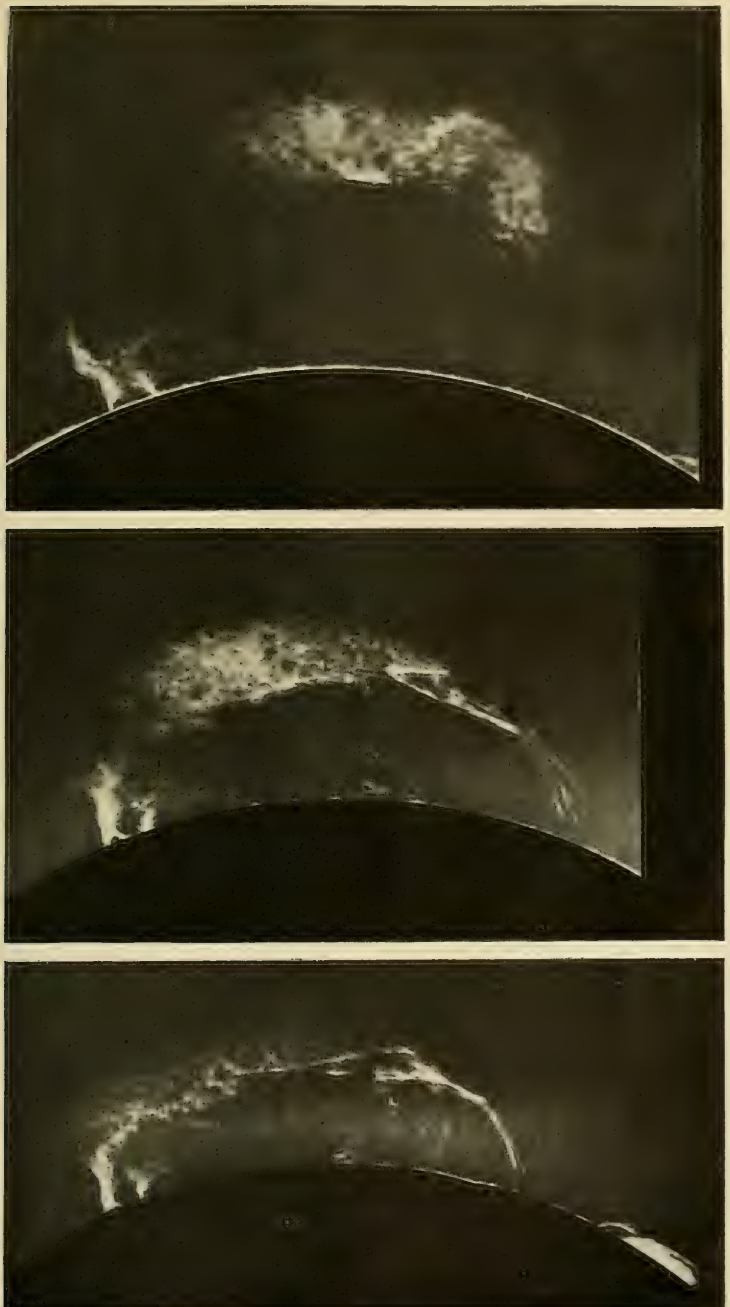
[1] *Carnegie Year Book,* No. 5 (1906), pp. 166 and 168.

[2] *The Origin of the Earth* (1916), p. 118.

Observatory by Pettit and associates.[1] These disclose motions of quite an astonishing nature. Fortunately for our purposes, the photographs were taken with one of the calcium lines, and as calcium has the atomic weight 40 and enters widely into the constitution of the earth body, its projection in this effective way has more significance than if it were one of the lightest elements. The general facts of the two cases are shown by Plates I and II, reproduced here from Plates IV and VI of Pettit's article. Both eruptions gave rise to archlike forms. The apex of each arch vanished while it was still ascending, the first disappearing at a height of 760,000 km. above the surface of the sun, the second at 720,000 km., that is, at heights somewhat more than the radius of the sun in each case. At the time of disappearance the first had an ascensive velocity of 60 km. per sec., the second, 163.9 km. per sec. Perhaps the most remarkable features disclosed were suddenly increased rates of ascent taken on at intervals, while the rates of ascent between these stages of increase were essentially *uniform.* Thus in the eruption of May 29, there was a rise, for 50,000 km., from a point 150,000 km. above the surface of the sun at a rate of 5.5 km. per sec., when the rate changed to 9.2 km. per sec., which was maintained for 119,000 km., when the velocity again changed to 27.9 km. per sec., which was held for 91,000 km., when the rate again increased to 60 km. per sec., which was maintained for 230,000 km. and was still being held when the prominence vanished, doubtless either by cooling or dispersion or both. In the eruption of July 15, it was found that from 200,000 km. to 294,000 km. above the sun's surface the rate of ascent of the center of the arch was 37 km. per sec.; at the latter height the velocity abruptly increased to 163.9 km. per sec., which was held for no less than 426,000 km., and was still retained at the disappearance of the projected mass.

However these extraordinary phenomena are to be explained, two significant things are implied: (1) that in some way the gravitation of the sun is offset or neutralized sufficiently to permit uniform motion, so far at least as the projected matter was con-

[1] Edison Pettit, "The Great Eruptive Prominences of May 29 and July 15, 1919," *Astrophys. Jour.*, L (October, 1919), pp. 206–19.



c
G.M.T.
$5^h 32^m 41^s$

b
$2^h 56^m 56^s$

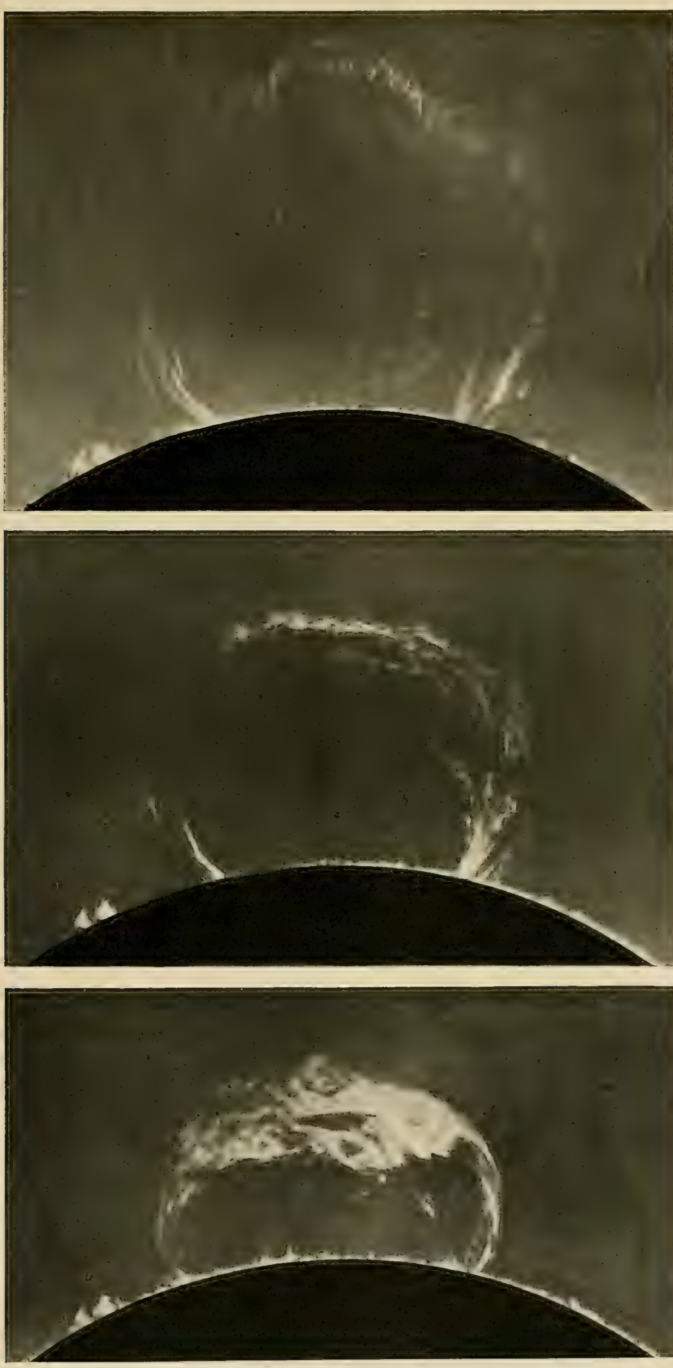
a
$1^h 41^m 16^s$

THE GREAT PROMINENCE OF MAY 29, 1919
Scale: for *a*, 1mm. = 9,326 km.; for *b* and *c*, 1 mm. = 8,416 km.
(After Pettit)

h
G.M.T.
$4^{h}7^{m}19^{s}$

g
$3^{h}51^{m}56^{s}$

f
$3^{h}8^{m}2^{s}$



THE PROMINENCE OF JULY 15, 1919
Scale: 1 mm. = 9,572 km.
(After Pettit)

cerned; and (2) that this matter received successive strong outward impulses, amounting in the last case to an increase of projection no less than 126.9 km. per sec. It is to be noted that this impulse was received after the arch had reached a height of 290,000 km. above the sun's surface. It is further to be observed that at the time the projections became invisible, in each case, more than half the restraining power of the sun, measured in terms of velocity, had been overcome. In the second case, the speed, at the time the projected matter became invisible, was competent to overcome more than half the remainder of the sun's restraining power.

Pettit finds data confirming these strange modes of movement, but of a less conclusive kind, in the photographs of certain other prominences already taken. He regards this singular mode of ascent by sudden accessions of speed with uniform motion between as the common one. However, none of these cases are sufficiently complete in themselves to show the full nature of these remarkable phenomena, for the ejected material passed out of sight while still under the highest observed uniform motion, and the extent to which this uniform motion may have continued and what followed it are left undetermined.

While further disclosures are required, and can only be awaited with eagerness, enough has already been revealed to give radical suggestiveness to these phenomena. They show that even at present and without obvious external stimulus there come into action, in addition to the internal eruptive forces, projectile forces of a high order which became effective at horizons high above the sun's surface, and that the combined projectile effect of these had overcome a large fraction of the restraining power of the sun before they passed out of sight.

Still another feature of the solar eruptions of May 29 and July 15, 1919, is scarcely less remarkable than their singular increments of motion. The projections on each of the two dates took the form of arches whose centers, at first low, rose impulsively into the forms shown on Plates I and II. The arch of May 29 was transverse to the sun's equator and had a chord of 584,000 km.; that of July 15 stood obliquely across the equator and had a chord of 363,000 km. as seen in perspective. The two ends of the arches appear

to have functioned quite differently. At one end, the arches seem to have sprung from short stumplike prominences that had been present for some time before the special eruptions of the dates named and remained for some time afterward. The movements of the calcium clouds near these seemingly originating ends were not only upward but inward toward the center of the arches. At the other end, the arches were apparently related to sun-spots. In these ends of the arches the calcium clouds seemed to be shooting swiftly toward the sun-spots. The photographs appear to show that special features in the upper part of the arches were drifting more or less from the prominence at the originating ends toward the sun-spot ends, though the motion of the central part of the arches was mainly upward. The total motions of the individual calcium molecules seem thus to have embraced a notable lateral component as well as the dominant ascensive one. The discovery by Hale and his associates that the cyclonic whirls associated with the sun-spots are negatively charged may perhaps be made to throw light on this. When ionization takes place by the discharge of an electrical element, it is usually the electron that is shot away, and the residual matter is then commonly positive. If, therefore, it be assumed that the calcium molecules shot forth from the stump prominences were positively charged, they would be drawn toward the negative charges of the sun-spot whirls.

A further feature of much interest is the suggestion of a rotational component in the projectile motion. This is implied in what has just been noted, a lateral movement combined with a vertical movement. A rather distinct expression of rotation seems to be shown in the spiraloid form of the upper central mass shown in Fig. *C*, Plate I. The value of this rotatory movement may be inferred from the fact that this spiraloid cloud had a volume more than 1,000 times that of the earth, assuming that its diameter in the line of vision was equal to the shorter of the two visible diameters.

While all these disclosures must remain *sub judice* until they have been amply verified and their interpretation made sure, it is permissible to bring their suggestiveness into service at once to mitigate the force of old views that always act as a drag upon new

views. These disclosures should help to lessen all hesitation in accepting the view that our atmosphere is even now receiving solar contributions. They should also lessen doubts as to the possibility of the projection of great masses of sun substance to planetary distances whenever stimulus is added to the spontaneous eruptivity of the sun.

MULTIPLE PHASES OF THE PLANETESIMAL HYPOTHESIS

In these new disclosures there is the germ of a new phase of the planetesimal hypothesis, a phase that may possibly dispense with aid from outside the solar system—heretofore supposed to be necessary—and so make the origin of planets a wholly domestic affair, though at present the suggestion does not look very promising. These disclosures seem to make the radial projection of the matter requisite for a planetary system possible without stimulus from outside. At the same time a *transverse* component of the projection is indicated in what has just been said about the lateral movement from the originating end of the arch toward the sun-spot end. If this lateral movement should prove adequate, and also be found to be preponderant in the right direction, it would contribute the component necessary to the revolution of the projected matter. The lateral movements in the two cases observed were chiefly across the equator of the sun, that is, normal to the required effect instead of coincident with it; but the position of the arches transverse to the line of sight in these two cases may be the essential reason why they were observed to such good effect. Similar movements in the line of sight, and in the direction of the sun's rotation, that is, the direction of planetary revolution, may not only be as common as these, but even be the predominant ones.

As the suggestion has only limited plausibility at present, it need not be further deployed here, but as it offers the possibility of a monoecious development of the planetary family in distinction from the dioecious origin heretofore postulated, even the shadow of such hypothesis is welcomed to a place among the multiple working sub-hypotheses that make up the planetesimal genus. Arranged with other developments of like order, the group of such sub-hypotheses embraces the following:

1. *Stimulus to eruptivity, as well as generation of tangential motion in the projected matter assigned to a passing star.*

   a) Star of medium mass and distance (one to five astronomical units, more or less). Original type, tested mathematically by half-hundred concrete trial cases.

   b) Giant star (in mass); distance great, tidal effect small, tangential effect large.

   c) Diminutive star, distance relatively small, tidal effect relatively large, tangential effect relatively small.

2. *Stimulus to eruptivity, as well as generation of tangential motion in the projected matter, assigned to some non-stellar body*, a stray planet for example. Approach to sun quite close, perhaps penetrating its Roche limit; tidal effect relatively great; adequacy of tangential effect less obvious, but assigned to the closeness with which the solar projections were shot out behind the passing body.

3. *Stimulus to eruptivity, as well as generation of tangential motion in the projected matter, assigned to a special concentration of gravitative stress in open space arising from two or more related bodies of large mass*, for example, the center of gravity between two stars, or the concentrated gravity-stress of star clusters in certain forms of arrangement.

4. *Actuating forces arising wholly within the solar system.* Projectile effects assigned to eruptive and projective forces within the sun; the tangential effects assigned to co-operative action of positive and negative centers in the sun as suggested above. Little more than a suggested possibility.

CRITICAL PHASES OF THE EVOLUTIONARY PROCESS

Let us follow that form of the planetesimal hypothesis whose working competency has been most fully tested. According to this the nuclei of the planets and satellites arose from solar eruptions—those of the planets from the central masses of such eruptions, those of the satellites from subsidiary masses that closely accompanied these and kept within their spheres of control. It is our special task to follow the nuclei of the four little bodies under study from their source in the sun to their organized states, having especially in mind those features that bear on the segregation of

heavy from light material, but it will be helpful to keep in mind bodies of both the larger and the smaller orders. So far as the selection and the segregation of matter is concerned, there was no essential difference between the planets and the satellites as such, for each arose from independent portions of the erupted sun substance. The critical elements were the spheres of control dependent on mass and dynamic environment.

While we must await further light on the precise modes in which solar gas-masses are shot forth and the circumstances that induce them, we may be quite sure that, as they passed away from the sun into the outer field of its control, certain influences inevitably affected them. They must have been under the control of a projectile force sufficient to overcome the larger portion of the sun's total attraction. In this controlling force we may safely assume that there were conjoined (1) an original projectile force having its origin in the interior of the sun, (2) radiation pressure from the sun after the mass had left its surface, and (3) electrical effects, attractive and repellent, as also ballistic, that is, due to the momentum of electrons and alpha particles shot forth from the sun and caught by the escaping mass. Just what proportionate parts these co-operating agencies played in the total work of projection, we need not now inquire. It is taken for granted, since it is almost inevitable, that in escaping from the sun the gas-masses acquired some measure of rotatory motion, in addition to the rotation they already had as parts of the sun; there may have been included some measure of vortex motion as most eruptions generate such motion. There can be no question that practically all the constituents of the outbursts were in the gaseous state as they emerged from the sun and that they carried in to the subsequent evolution the molecular activities common to hot gases. The several projectile motions were more or less independently imposed on the emerging mass, and later these underwent more or less independent increases and declines, so that an important part of the ensuing evolution consisted in their mutual adjustment to one another. At the outset, the projectile velocity greatly preponderated over the velocities of all other motions, and until this became adjusted so as to be approximately proportionate to all

integers of the mass it was a prime source of turbulence and danger of dispersion. In so far as molecules were driven by it beyond the sphere of control of the common mass, they took courses of their own and, in the main, either returned by elliptical paths to the sun or became planetesimals. The danger of dispersion at this stage was a serious menace to all the minor masses whose self-control was feeble; at the same time it was a prolific source of planetesimal food for the growth of the nuclei later.

The hypothesis assumes that a part of the out-shot masses contained matter enough to give them self-control. The effectiveness of their control increased as they passed from the more intense to the less intense field of the sun's control, except as they lost material. But such self-control is not postulated of more than a part—probably less than half—the matter projected from the sun, the more scattered portion becoming planetesimals at once or else returning to the sun. Effective self-control is only assigned to a few of the greater eruptions, or, to be specific, to four of the major order, to form the nuclei of the four giant planets, and to four of the minor order, to form the nuclei of the terrestrial planets. But subordinate to these, perhaps a thousand or so little knots succeeded in holding themselves together and later grew into planetoids and satellites. It is thus assumed that there arose, as a result of eruptive projection and partial dispersion, a graded series of knots ranging from those that were massive enough to form the nuclei of the great planets down through medium and smaller knots to masses too small to hold themselves together in the face of the dissipating influences. It was of course in the lower ranges of this graded series that there arose the more critical questions of self-control and of permanent maintenance. The answers to these critical questions hung, in each individual case, very largely upon gravitative competency.

Now we need not dwell on the largest order of knots, for they do not enter our problem. Their strong attractions enabled them to hold their own, except for a small percentage of molecules that attained exceptional cumulative speeds, while, on the other hand, they were able to pick up stray planetesimals that came within their spheres of control in a favorable way. And so in the end,

between their ability to hold all sorts of molecules as well as pick them up, they came to have a much larger proportion of light molecules than the smaller bodies which could only hold the heavier ones, and so they now have relatively low specific gravities. Their great size helped them to remain hot, which also contributed to their low specific gravities. The largest of these is now more than three hundred times as massive as the largest of the terrestrial group; the mean mass of the giant planets is more than two hundred times the mean mass of the terrestrial planets. Our problem then is with a group of distinctly small bodies in which the balance between holding and non-holding power was more critical, and we need to enter somewhat more into detail.

1. As the material was shot forth from the sun, it was an intimate mixture of solar molecules of various kinds in a very hot gaseous form, and the molecules were interacting upon one another at speeds inversely proportional to the square roots of their molecular weights. In the process of forming definite knots under self-control out of the less-defined solar outbursts, of which a considerable part was dissipated into planetesimals or fell back to the sun, the lighter molecules of high speed would be more likely to be dissipated than the heavy ones of lesser speed, but we need not insist on that, as the dispersing danger came from the projectile force and probably was not very selective.

2. But when that contingency was passed and each knot began its own independent evolution, there arose a very definite selective process within the knot itself. We assume that for a short time the knots would still be hot and diffuse, and that during this stage there would be larger chances for molecules to escape from the control of the knot than later (*a*) because their velocities were highest on account of temperature, and (*b*) because their deployment was relatively open so that the molecules were less in one another's way when they happened to accumulate velocity enough to escape from control. We assume that this was the most crucial stage of the knot, and that selective loss was then its greatest danger. The lightest molecules, because they had the highest mean speeds and most frequently encountered and divided energies with other molecules, were those that most often acquired cumulative speeds

enough to enable them to escape. In each encounter there was an equi-partition of energy and the light molecules were given superior speeds in compensation for their lack of mass. The action was thus a highly selective process.

But lest we seem to overstress this depleting process, let it be noted that for every reaction that gave exceptional speed to a light molecule there was a reaction in a counter-direction that gave to the heavier partner in the encounter a lower velocity. And further, it was only in the outer border of the knot that the lighter molecule rebounding outward could usually find a way of escape without another collision and a rebound in the wrong direction, and so the effect of the counter-reaction was to drive a heavier molecule inward for every case in which a lighter molecule escaped. This tended to herd in the heavier molecules and make their mutual attraction more effective, while they were inherently more amenable to control. There was a loss of mass, to be sure, but there was a more than compensating loss of dissipating activity and the residue was more congenial to control.

Taking the knot as a whole, then, there was a steady progress toward a higher average of heavier molecules, and toward an assemblage more amenable to control. Those knots which had been given masses enough to endure this process soon reached a stage of safety and then began to build up by capturing such planetesimals as they could control. Those knots that could not endure the process dispersed into planetesimals or erratic wanderers. The hypothesis, of course, assumes that the nuclei of our four bodies had original masses enough to live through this critical stage, as did also those of all the planetoids and satellites, but it favors the belief that the smallest planetoids and satellites represent the lower limit of successful knots, for if still smaller ones were successful we might expect to see their representatives in the heavens about us. The giant hot stars are, of course, the greatest known examples of success in holding light, hot gases by self-gravity. The multitude of these are our assurance that the principle of gaseous self-control is sound and that it has realization of the highest order in the great cosmos.

It scarcely need be added that the severest selection of heavy molecules would be realized in the smallest knots where the struggle to maintain themselves was most strenuous, and that in the intermediate class the percentage of heavy molecules would be inversely proportional to mass.

All this relates to the purely molecular state assumed to prevail while the knots were organizing themselves out of solar ejections and were beginning their careers as the nuclei of growth into mature planets, planetoids and satellites.

3. Let us turn now to the inner evolution of these nuclei. Let us recall that immediately on the emergence of the gas-masses from the sun there was great expansion and much cooling in consequence. Rapid radiation must have followed as the expanded mass shot out into the relatively cold space of the outer regions. It seems inevitable therefore that the condensation temperatures of the refractory material that now makes up most of the solid body of the earth, and doubtless of its neighbors, would be reached at a succession of stages relatively early in the history of the medium and smaller order of knots. We may assume that the condensation into minute spherules was started by electric charges and followed essentially the lines already sketched in the study of the derivatives from a rotating spheroidal nebula. There was this difference, however. The centrifugal derivatives from the rotating nebula were planetesimals each following its own orbit. The condensations within the nuclei were, at first at least, scattered through the uncondensed portion that was still gaseous. The condensed spherules or crystals were like cloud particles or dust particles in an atmosphere. Dynamically they were like Brownian particles, jostled about by the impacts of the molecules that still remained in the gaseous state. They would naturally develop earliest in the outer parts of the nuclei and later in the inner parts. They would constitute a class of bodies heavier than the molecules and would tend to damp molecular action, while they themselves would tend to fall toward the center of the nuclei, but their fall would be resisted by the part that remained gaseous. It is obvious that the condensation of the refractory heavy material into spherules or

crystals in the midst of the gaseous molecules would mark the turn of the tide in the history of the smaller nuclei for the molecular losses would speedily grow less and a definite centralizing movement would set in which would increase the power of self-control. Molecular losses would be lessened and the capture of planetesimals increased relatively.

The question of the temperatures and the physical states that would follow this stage in the smaller nuclei is important and difficult but must be deferred.

4. It remains only to consider the selective action of the successful nuclei in the process of gathering in planetesimals, but this need not detain us for the principles would be essentially those already emphasized sufficiently. The smaller order of nuclei could not capture and hold the lighter free molecules as such, though they could perhaps capture and retain the very heavy molecules. They could quite certainly hold most of the planetesimal aggregates that they encountered but would have little power to draw them to themselves. The nuclei of medium mass could hold some of the free molecules but not the lightest, and so their accessions would be greater in mass, but lower in mean specific gravity.

SUMMARY

It seems clear, then, from the foregoing considerations that, *in general, the planets, planetoids, and satellites, if built up by the planetesimal method, would be composed of inherently heavy material in inverse proportion to their masses*, and hence that the inherent specific gravity of the matter of the moon would be somewhat greater than that of Mars, that of Mars somewhat greater than that of Venus, and that of Venus greater than that of the earth.

There is still need to consider (1) what were the physical states of the nuclei while they were gathering in the planetesimals, (2) what masses the planetesimals attained, and (3) what was the effect of their infall on the later stages of the growing bodies. This last will obviously involve the frequency of the fall of the planetesimals upon the nuclei. The discussion of these points must be deferred to the next article.

It may be noted, however, that the physical state of the matter, whatever it may be, will not radically affect the mean constitution of the bodies, though it is liable to affect greatly the distribution of the material. Reserving judgment on any shrinkage effect that may arise from such difference of distribution, we may note that the inquiries of this paper, in harmony with the suggestions of the previous paper, very distinctly imply that, if the moon, Mars, Venus, and the earth were built up normally by the planetesimal method, they should contain proportions of inherently heavy material in the inverse order of mass. There is therefore corresponding reason to think that the estimate of the total shrinkage of the earth deduced in the preceding article will need to be somewhat increased, as anticipated, on account of the differences of material that make up the four bodies compared.

A QUANTITATIVE MINERALOGICAL CLASSIFICATION OF IGNEOUS ROCKS—REVISED

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PART II

CLASS 2, ORDER I

(210) **Meso-silexite.** See note under (110).

(211) **Moyite.** The rocks of this family are quartz-orthogranites. Since three of the rocks described by Daly[1] from the Moyie sill along the Forty-ninth Parallel are of this uncommon type, the term moyite is here suggested for the family name.

(215) Rockallite JUDD. The name rockallite is derived from the Island of Rockall, off the coast of Ireland. Judd[2] describes the rock as composed of aegirite, quartz, and albite. While the presence of aegirite makes the rock abnormal, the term may be used, at least temporarily, for the family name. Rockallite is a quartz-rich aegirite-albite-tonalite.

(216) **Orthogranite.** This is a comparatively rare rock, only differing from normal granite in containing no plagioclase. In this group also belong anorthoclase-granite, potash-rhyolite (**ortho**rhyolite), comendite, and some grorudites and solvsbergites. Many of the granites belonging here are aegirite- or riebeckite-bearing. For the use of the prefix "ortho-" see (111).

Microcline-granite.
Anorthoclase-granite.
Orthogranitite.

[1] Reginald A. Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Geol. Surv. Canada, Mem. 38*, Part I, pp. 229, 230, 231.

[2] J. W. Judd, "On the Petrology of Rockall," *Trans. Royal Irish Acad. Dublin*, XXI (1897), 49–57.

Orthorhyolite is the extrusive equivalent of this family.

Comendite BERTOLIO[1] is an aegirite-rhyolite.

Paisanite OSANN. Paisanite was named from Paisano Pass, Texas, by Osann.[2] It is a dike rock composed of quartz, microperthite, and riebeckite.

(217) Albite-granite. The term albite-granite is here applied to a normal granite containing orthoclase and plagioclase between the proportions 95:5 and 65:35. The plagioclase, however, is albite, and not the usual oligoclase. A new name should be chosen, since the terms soda-granite, albite-granite, albite-syenite, etc., have been used for rocks with albite as the only feldspar, that is, for rocks which properly are called albite-tonalite, albite-diorite, etc., in this classification.

Albite-rhyolite. The extrusive equivalent of the preceding. The objection to the term albite-granite applies also to albite-rhyolite.

(218) **Albite**-adamellite. No confusion can result from the use of this term, since adamellite conveys the idea of a quartz-monzonitic rock, and the prefix indicates that the plagioclase of the orthoclase-plagioclase combination is albite. A number of grorudites fall here, as does also a lindoite, and numerous arfvedsonite- and riebeckite-granites, so called.

Albite-dellenite. The extrusive of the preceding.

(219) **Albite**-granodiorite. There is no possibility of misunderstanding this name. See notes under (218) and (229).

Albite-rhyodacite. See note under (229).

(2110) **Albite**-tonalite. The meaning of this term also is unmistakable. See note under (217). For the use of tonalite for quartz-diorite see (2210).

Albite-dacite. The extrusive of preceding.

[1] S. Bertolio, "Sulle comenditi, nuovo gruppo di rioliti con aegirina," *Atti. della Reale Accad. dei Lincei, Cl. scienze fisiche, mat. e nat.*, IV (1895), 2 semestre, pp. 49–50.

[2] A. Osann, "Report on the Rocks of Trans-Pecos, Texas," *4th Ann. Rept. Geol. Surv. Texas* (1892), p. 132.

(2111) **Orthosyenite.** This family includes syenites with orthoclase, microcline, microperthite, or anorthoclase, but with less than 5 per cent plagioclase.

Orthotrachyte. The extrusive equivalent of the preceding.

(2112) Albite-syenite. A term less likely to be misunderstood should be chosen for this family. See note under (217).

Albite-trachyte. See note under (217).

(2113) **Albite-monzonite.** This term cannot be misunderstood. See note under (218).

Albite-latite. The extrusive equivalent of the preceding.

(2114) **Albite-monzodiorite.** See note under (218). For the use of monzodiorite see (2214).

Albite-andelatite. The extrusive equivalent of the preceding. See note under (2214).

(2115) **Albite-diorite.** This term also is unmistakable. The word diorite conveys the impression of a plagioclase rock, and the prefix suggests that this feldspar is albite. The term soda-syenite has been used for this rock, but it was badly chosen. Soda-syenite naturally suggests a syenite rich in soda feldspar, but not to the exclusion of orthoclase. Albite-diorite is a much better term.

Albite-andesite. The extrusive equivalent of the preceding.

(2116) Pulaskite Williams. This term is used in the sense of Williams'[1] original definition: "a rock made up of orthoclase, pyroxene, amphibole, and *a little* eleolite or its decomposition product, analcite." In another place[2] he says that the orthoclase is "similar to Brögger's kryptoperthite, although the amount of soda is somewhat less than is usually found in this." The rock, therefore, clearly falls into (2116), for while the dark constituents are not prominent they are greater than 5 per cent, as was shown by the examination of various thin sections from the type locality. Brögger's[3] type laurvikite belongs here, but the

[1] J. Francis Williams, "The Igneous Rocks of Arkansas," *Ann. Rept. Geol. Surv. Arkansas for 1890*, II, 20.

[2] *Ibid.*, p. 60.

[3] W. C. Brögger, *Die Eruptivgesteine des Kristianiagebietes. III: Das Ganggefolge des Laurdalits* (Kristiania, 1898), p. 30.

characteristic texture of this rock excludes it from representing the family.

(2121) **Ortho**-nephelite-syenite, **ortho**-leucite-syenite. This is nephelite- (or leucite-) syenite without plagioclase.

Orthofoyaite. See note under (2222).

Orthoditroite. See note under (2222).

Orthophonolite. The extrusive equivalent of the preceding.

(2122) **Albite**-nephelite-syenite, **albite**-leucite-syenite. Nephelite-(leucite-) syenites carry orthoclase either as the only feldspar or in combination with plagioclase, which may be albite or some other member of the series. In this family (2122) belong those carrying albite.

Albite-foyaite. See note under (2222).

Albite-ditroite. See note under (2222).

Albite-phonolite. The extrusive corresponding to the preceding.

(2123) **Albite**-nephelite-monzonite. Here belong numerous tinguaites and so-called nephelite-syenites, also a sodalite-foyaite and a cancrinite-syenite. Covite Washington, according to the calculated mode, belongs here, but under the definition Washington[1] says the rock is a "leucocratic combination of orthoclase and less nephelite with hornblende and aegirite-augite," which would place it in Family 21.

(2124) Litchfieldite Bayley. In his description of litchfieldite Bayley[2] says: "As was indicated by the microscopic study, no plagioclase other than albite is present, and this, as seen (from a calculated mode), is largely in excess of the orthoclase." The mode computed from the analysis indicates 27 per cent orthoclase and microcline, 47 per cent albite, 17 per cent nephelite, and 2 per cent cancrinite. These proportions are about the same as shown by the thin section and Thoulet separation. While cancrinite occurs in the type rock, Bayley[3] says: "I do not regard

[1] Henry S. Washington, "The Foyaite-Ijolite Series of Magnet Cove: A Chemical Study of Differentiation," *Jour. Geol.*, IX (1901), 615.

[2] W. S. Bayley, "Eleolite-Syenite of Litchfield, Maine," *Bull. Geol. Soc. Amer.*, III (1892), 242.

[3] *Ibid.*, *In litteris*, June 14, 1919.

cancrinite as an essential constituent . . . . and many of the specimens show none. . . . . Some of it is certainly secondary." The rocks of this family may therefore be divided into

Litchfieldite (normal).

Cancrinite-litchfieldite.

The calculated mode of canadite QUENSEL[1] places it in this family, but the actual mineral composition may be quite different. Quensel[2] says that "a rock entirely consisting of nephelite, albite, and a mafic mineral may or may not be a canadite, depending upon the presence or absence of a certain amount of normative lime-feldspar." Depending thus upon chemical composition for its name, it is excluded here.

(2125) Mariupolite MOROZEWICZ. Morozewicz[3] described certain rocks from the shores of the Sea of Azof which consist of much albite, less nephelite, and some ferromagnesian constituents and zircon. He gives two modal analyses, determined microscopically, both of which fall in this family somewhat above the center point.

(2126) Naujaite USSING. Several nephelite- and leucite-syenites belong here, as does also arkite WASHINGTON.[4] The latter, however, is too poor in feldspar to be typical of the family, and it carries garnet as an essential. Naujaite USSING[5] is the rock originally described by Steenstrup[6] as a sodalite-syenite. Pending the location of a nephelite-rich orthofoyaite or orthoditroite, naujaite may represent the family.

Syn.: Sodalite-syenite STEENSTRUP.

Arkite WASHINGTON.

[1] Percy Quensel, "The Alkaline Rocks of Almunge," *Bull. Geol. Inst. Upsala*, XII (1914), 135, 176–77.

[2] *In litteris*, May 16, 1915.

[3] J. Morozewicz, "Über Mariupolit, ein extremes Glied der Eleolithsyenite," *Tscherm. Min. Petr. Mitth.*, XXI (1902), 245.

[4] Henry S. Washington, "The Foyaite-Ijolite Series of Magnet Cove: A Chemical Study in Differentiation," *Jour. Geol.*, IX (1901), 617.

[5] N. V. Ussing, "Geology of the Country around Julianehaab, Greenland," *Meddel. om Grönl.*, XXXVIII (1911), 32, 143–56.

[6] K. J. V. Steenstrup, "Bemaerkninger til et geognostisk Oversigtskaart over en Del af Julianehaabs Distrikt (den 20 Juni 1878)," *Meddel. om Grönl.*, II (1881), 35.

(2127) **Beloeilite.** O'Neill[1] described a "feldspathic tawite" from Mount St. Hilaire (Beloeil), Quebec, intermediate in composition between sodalite-syenite and tawite. This rock may be called beloeilite and may serve as the type of the sodalite rocks of the family.

(2129) A soda-sussexite of Hackman[2] and a nephelite-sodalite-syenite of O'Neill[3] belong here.

(2130) **Toryhillite.** Adams and Barlow[4] described a nephelite-rich albite rock from Toryhill, Monmouth Township, Ontario. The rock falls near the center point of this family; therefore a new name is here suggested.

(2131) Urtite RAMSAY. Urtite is a feldspar-free nephelite rock, described by Ramsay.[5] The name is derived from the second part of Lujavr-Urt, where the rock was first found. It consists of 82 to 86 per cent nephelite, 12 to 18 per cent aegirite-augite, and 2 per cent apatite. Ijolite RAMSAY and BERGHELL,[6] with 51.6 per cent nephelite, and monmouthite ADAMS and BARLOW,[7] with 77.6 per cent feldspathoid (of which 72 is nephelite), also belong here. The leucite rock of this family is fergusite PIRSSON.[8] Only a single occurrence is known. It consists of 65 per cent pseudoleucite and 35 per cent mafites, chiefly diopside. The melilite rock of the family is represented by uncompahgrite LARSEN.[9] It is a

[1] J. J. O'Neill, "St. Hilaire (Beloeil) and Rougemont Mountains, Quebec," *Geol. Surv. Canada, Mem. 43* (Ottawa, 1914), p. 46.

[2] V. Hackman, "Neue Mitteilungen über das Ijolithmassiv in Kuusamo," *Bull. d. l. Comm. Geol. d. Finlande,* No. 11 (Helsingfors, 1899), p. 24.

[3] J. J. O'Neill, *op. cit.*, p. 41.

[4] Frank D. Adams and Alfred E. Barlow, "Geology of the Haliburton and Bancroft Areas, Province of Ontario," *Geol. Surv. Canada, Mem. 6* (1910), p. 273.

[5] Wilhelm Ramsay, "Urtit, ein basisches Endglied der Augit-syenit-Nephelinsyenit-Serie," *Geol. Fören. i. Stockh. Förhandl.*, XVIII (1896), 463.

[6] Wilhelm Ramsay and Hugo Berghell, "Das Gestein vom Iiwaara in Finland," *Geol. Fören. i. Stockh. Förhandl.*, XIII (1891), 304; also V. Hackman, *op. cit., supra,* p. 20.

[7] Frank D. Adams and Alfred E. Barlow, *op. cit.*, p. 277.

[8] Louis Valentine Pirsson, "Petrography and Geology of the Igneous Rocks of the Highwood Mountains, Montana," *U.S. Geol. Surv., Bull. 237* (1905), p. 88.

[9] Esper S. Larsen, "Melilite and Other Minerals from Gunnison County, Colorado," *Jour. Wash. Acad. Sci.*, IV (1914), 473.

deep-seated rock consisting of two-thirds melilite and one-third dark constituents (magnetite and pyroxene) with some accessory perofskite and apatite. The extrusive equivalent is melilite-basalt STELZNER[1] (Syn. Melilithit LOEWINSON-LESSING[2]).

CLASS 2, ORDER 2

(222) **Quartz-**granite. Since the term granite in itself carries the idea of a quartz-bearing rock, the term quartz-granite will indicate a granite that is rich in quartz. All other rocks which, by definition, carry quartz may be similarly qualified, namely, adamellite, granodiorite, tonalite, etc.

(223) **Quartz-**adamellite. See note under (222). Here belongs, though far from the center point, the Hauksuo, Kisko, aplite, described by Eskola,[3] which consists of quartz 48.9 per cent, plagioclase (average $Ab_{85}An_{15}$) 22.9 per cent, microcline 20.4 per cent, biotite 4.4 per cent, magnetite 1.9 per cent, and epidote 1.5 per cent.

(224) **Quartz-**granodiorite. See note under (222).

(225) **Quartz-**tonalite. See note under (222). For the use of tonalite for quartz-diorite see (2210).

(227) Granite. This term is of very old date. It is not found in Pliny. Breislak says it was first used by Caesalpinus[4] in 1596. The name may be derived from the Italian *granito*, "grained" (Lat. *granum*), but its origin is uncertain. The word is similar in sound in many languages, for example, *gwenith faen* ("wheat stone") in Welsh, and it is possible that the name was brought from Wales by the Romans who built roads and worked the mines there about 78 A.D.

Family (227) is that of the normal granites. These rocks consist of quartz, orthoclase, less oligoclase or andesine, and a moderate

[1] Alfred Stelzner, "Mittheilungen an den Redaction," *Neues Jahrb.*, I (1882), 230–31; also "Über Melilith und Melilithbasalte," *Neues Jahrb., B.B.*, II (1882), 364–440.

[2] F. Loewinson-Lessing, "Kritische Beiträge zur Systematik der Eruptivgesteine, IV," *T.M.P.M.*, XX (1901), 114.

[3] Pentti Eskola, "On the Petrology of the Orijärvi Region in Southwestern Finland," *Bull. d. l. com. géol. d. Finlande*, No. 40 (1914), p. 83.

[4] Andreas Caesalpinus (Cesalpino), *De Metallicis* (1596), II, cap. 11.

amount of mafic minerals. There are many subfamilies, depending upon the accessories or dark constituents.

Granitite. This is an old term which has been used with a great variety of meanings. So long ago as 1823 von Leonhard[1] said that the proposal to call granites with accessory minerals granitite was superfluous and unfitting. Rose[2] used the word for muscovite-free biotite-bearing rocks with quartz, orthoclase, and considerable oligoclase. It was used in the same sense by Senft[3] and Rosenbusch,[4] and is here also used as a synonym for biotite-granite. Cathrein's[5] suggestion that it be used for plagioclase-rich hornblende-bearing granites has never been followed.

Amphibole-granite.

Arfvedsonite-granite Brögger.[6]

Augite-granite.

Binary-granite Keyes[7] contains both muscovite and biotite. It is also called two-mica granite.

Hypersthene-granite.

Syn.: Charnockite Holland.[8]

Microcline-granite.

Muscovite-granite.

Tourmaline-granite, etc.

Rhyolite von Richthofen. The name rhyolite (from ῥύαξ, "lava stream," "torrent") was given by von Richthofen[9] to the extrusive equivalent of granite on account of its usual fluidal

[1] K. C. von Leonhard, *Charakteristik der Felsarten* (Heidelberg, 1823), I, 54.

[2] Gustav Rose, "Ueber die zur Granitgruppe gehörenden Gebirgsarten," *Zeitschr. d. d. geol. Ges.*, I (1849), 386; also pp. 363–66.

[3] Ferdinand Senft, *Classification und Beschreibung der Felsarten* (Breslau, 1857), p. 297.

[4] H. Rosenbusch, *Mikroskopische Physiographie der massigen Gesteine* (1st ed.; Stuttgart, 1877), II, 20–21.

[5] A. Cathrein, "Zur Dünnschliffsammlung der Tiroler Eruptivgesteine," *Neues Jahrb.*, I (1890), 72.

[6] W. C. Brögger, "Die Mineralien der Syenitpegmatitgänge der südnorwegischen Augit- und Nephelinsyenite," *Zeit. f. Kryst.*, XVI (1890), 68.

[7] Charles Rollin Keyes, "Origin and Relations of Central Maryland Granites," *U.S. Geol. Surv., Ann. Rept.*, XV (1895), 714.

[8] T. H. Holland, "The Charnockite Series, a Group of Archean Hypersthenic Rocks in Peninsular India," *Mem. Geol. Surv. India*, XXVII (1900), 2, 119.

[9] Ferdinand Freiherrn v. Richthofen, "Studien aus den ungarisch-siebenbürgerischen Trachytgebirgen," *Jahrb. d. k. k. geol. Reichsanst.*, XI (1860), 156.

character. Roth[1] called the same rocks liparites, from the Lipari Islands, where they occur.

Syn.: Liparite ROTH.

Nevadite VON RICHTHOFEN. Nevadite is a variety of rhyolite with very abundant phenocrysts and very little groundmass. It was named by von Richthofen[2] from its occurrence in Nevada.

(228) Adamellite CATHREIN-BRÖGGER. The term adamellite is here given to quartz-monzonites. It was originally used by Cathrein[3] for rocks from Adamello which contain both orthoclase and plagioclase. Speaking of these rocks he says: "Er ist ein lichtes, schon im Aussehen mehr den Graniten als Dioriten sich näherndes Gestein." Brögger[4] uses the name for acid quartz-monzonites, and Ball[5] and Hatch[6] use it for quartz-monzonite.

Syn.: Quartz-monzonite BRÖGGER.

Windsorite DALY.[7] This is a quartz-poor quartz-monzonite dike-rock.

Dellenite BRÖGGER. The rock intermediate between dacite and rhyolite from Dellen, Helsingland, Sweden, was named dellenite by Brögger,[8] and the term is here used for the extrusive equivalent of quartz-monzonite. Since it consists of a single word it is preferable to quartz-latite.

Syn.: Quartz-latite RANSOME,[9] Dacite-liparite BRÖGGER.[10]

[1] Justus Roth, *Gesteinsanalysen*, xxxiv (1861).

[2] F. Baron von Richthofen, "Principles of the Natural System of Volcanic Rocks," *Mem. Cal. Acad. Sci.*, I (1868), Part II, p. 16.

[3] A. Cathrein, "Zur Dünnschliffsammlung der Tiroler Eruptivgesteine," *Neues Jahrb.*, I (1890), 74.

[4] W. C. Brögger, *Die Eruptivgesteine des Kristianiagebietes. II: Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol* (Kristiania, 1895), p. 61.

[5] Sydney H. Ball, "General Geology of the Georgetown Quadrangle, Colorado," *U.S. Geol. Surv. Wash., Prof. Paper 63* (1908), p. 51.

[6] F. H. Hatch, *The Petrology of the Igneous Rocks* (London, 1914), p. 176.

[7] R. A. Daly, "The Geology of Ascutney Mountain, Vermont," *U.S. Geol. Surv., Bull. 209* (1903), p. 46.

[8] W. C. Brögger, *Die Eruptivgesteine des Kristianiagebietes. II: Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol* (Kristiania, 1895), p. 59, note.

[9] F. Leslie Ransome, "Some Lava Flows of the Western Slope of the Sierra Nevada, California," *Amer. Jour. Sci.*, V (1898), 372.

[10] W. C. Brögger, *op. cit.*, p. 60.

(229) Granodiorite BECKER. The term granodiorite was suggested by Becker[1] for plutonic rocks containing both orthoclase and acid plagioclase, the latter in excess of the former. The name was first published in a paper by Lindgren[2] in 1893 and described in more detail later.[3] Lindgren[4] says: "The truly characteristic feature of the granodiorites is that the soda-lime feldspar, which always is a calcareous oligoclase or an andesine, is *at least* equal to double the amount of the alkali feldspar. The latter may be taken to vary from 8 per cent to 20 per cent" in a rock with an assumed feldspar content of 60 per cent.[5] "Below the lower limit the rock becomes a quartz-diorite: above the upper a quartz-monzonite." "In the quartz-monzonite," he continues, "I would give this mineral a range from 20 per cent to 40 per cent," again assuming a total of 60 per cent feldspar. His divisions, therefore, based on the orthoclase-plagioclase ratio are $0–13\frac{1}{3}–33\frac{1}{3}–66\frac{2}{3}$ for quartz-diorite, granodiorite, and quartz-monzonite. In the present classification the divisions are taken at 0–5–35–65, the writer believing that more than 5 per cent of orthoclase changes the character of a quartz-diorite too much for it to retain that name. Setting apart as orthogranite the rock with 95 to 100 per cent of its feldspar orthoclase, and as quartz-diorite that having 95–100 per cent plagioclase, the remaining 90 parts are divided into three

[1] Waldemar Lindgren, "Granodiorite and Other Intermediate Rocks," *Amer. Jour. Sci.*, IX (1900), 270.

[2] *Ibid.*, "The Auriferous Veins of Meadow Lake, California," *Amer. Jour. Sci.*, XLIV (1893), 202.

[3] *Sacramento Folio, U.S. Geol. Surv.*, No. 5, 1894; *Placerville Folio*, No. 3, 1894; *Smartsville Folio*, No. 18, 1895; *Nevada City Folio*, No. 29, 1896; *Pyramid Peak Folio*, No. 31, 1896; *Truckee Folio*, No. 39, 1897; H. W. Turner, "The Rocks of the Sierra Nevada," *U.S. Geol. Surv.*, An. 14, pp. 478, 482; Waldemar Lindgren, "The Gold-Silver Veins of Ophir, California," An. 14, *U.S. Geol. Surv.*, Part II (1894), pp. 252, 255–56; also "The Gold Quartz Veins of Nevada City and Grass Valley Districts, California," An. 17, *U.S. Geol. Surv.*, Part II (1896), p. 35; "The Granitic Rocks of the Pyramid Peak District, Sierra Nevada, California," *Amer. Jour. Sci.*, III (1897), 308; "The Granitic Rocks of Sierra Nevada," *Abstr. in Science*, New Series, V (1897), 361; "Granodiorite and Other Intermediate Rocks," *Amer. Jour. Sci.*, IX (1900), 269–82.

[4] Waldemar Lindgren, "Granodiorite and Other Intermediate Rocks," *Amer. Jour. Sci.*, IX (1900), 277.

[5] *Ibid.*, p. 279.

equal portions, one each for normal granite, quartz-monzonite, and granodiorite.

The term granodiorite is not the most satisfactory, from the standpoint of the construction of the word, for a rock intermediate between quartz-monzonite (adamellite) and quartz-diorite (tonalite), for it suggests a rock intermediate between a granite (an orthoclase-quartz-bearing rock) and a diorite (a plagioclase-quartz-free rock), that is, a quartz-monzonite. Monzonite in the sense in which we now use it, however, was not introduced by Brögger until 1895, while granodiorite was first used in 1892 or 1893. The term was intended to convey the idea of a diorite with granitic characters, that is, with quartz and a certain amount of orthoclase, but upon the introduction of the term monzonite Lindgren[1] found it advisable to restrict the "definition of granodiorite to rocks considerably nearer quartz-diorite than originally intended." A name derived from the rocks between which granodiorite, as now defined, actually stands would give adam-tonalite, which is hardly euphonious, to say the least. Furthermore, the term granodiorite is so firmly established and was so clearly defined that it should not be changed.

The term banatite was used by Brögger[2] for his intermediate quartz-monzonites, and under this term are included rocks which are probably to be classed as quartz-poor granodiorites (see under 2213).

The objection to the construction of the word granodiorite as applied to rocks under the present definition applies also to the terms introduced by the present writer[3] in 1917, namely granogabbro, syenodiorite, and syenogabbro. But since granodiorite is retained for the reasons stated above, and adam-gabbro is as objectionable as adam-diorite, granogabbro (239) also will be retained to make analogous terms. The names of the extrusive rocks should naturally conform in construction to their deep-seated equivalents; consequently rhyodacite Winchell is used for the

[1] Waldemar Lindgren, *In litteris*, June 17, 1919.

[2] W. C. Brögger, *Die Eruptivgesteine des Kristianiagebietes. II: Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol* (Kristiania, 1895), p. 60.

[3] Albert Johannsen, "Suggestions for a Quantitative Mineralogical Classification of Igneous Rocks," *Jour. Geol.*, XXV (1917), p. 89.

granodioritic extrusive, and rhyobasalt is here proposed for the granogabbroic. Syenodiorite and syenogabbro will be replaced by the better terms monzodiorite and monzogabbro. For the corresponding extrusives, ande-latite and basa-latite are here proposed.

Rhyodacite WINCHELL.[1] See note under granodiorite above. This is the extrusive equivalent of granodiorite.

(2210) Tonalite VOM RATH-BRÖGGER-SPURR. Tonalite was applied by vom Rath[2] to a certain rock from Monte Tonale, in the Tyrol. It consists of abundant quartz, andesine, very small amounts of orthoclase as an accessory, and a dark mineral. In the definition, however, vom Rath omitted the orthoclase, which occurs as micropegmatite and was regarded simply as an accessory, and said: "Der Tonalit enthält in körnigem Gemenge als wesentliche Bestandtheile: eine trikline Feldspath-Species, Quarz, Magnesiaglimmer und Hornblende." In his tabulation Brögger[3] used tonalite for acid quartz-diorite, and in another place[4] he said: "Der Name Tonalit wäre dann den Quarzdioriten vorbehalten." Since Brögger does not use the subdivision granodiorite, his tonalite includes some of these rocks. Simply as quartz-diorite the term was used by Spurr,[5] who adopted it as a group name instead of quartz-diorite, because it "is shorter and more characterizing." In the same sense it was used by Winchell[6] and Hatch,[7] and it is so used here.

Incidentally, the average igneous rock of Clarke,[8] computed into common minerals, falls in this family. It contains quartz

[1] Alexander N. Winchell, "Rock Classification on Three Co-ordinates," *Jour. Geol.*, XXI (1913), 214.

[2] G. vom Rath, "Beiträge zur Kenntniss der eruptiven Gesteine der Alpen," *Zeitschr. d. d. geol. Ges.*, XVI (1864), 250.

[3] W. C. Brögger, *Die Eruptivgesteine des Kristianiagebietes. II: Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol* (Kristiania, 1895), p. 60.

[4] *Ibid.*, p. 61.

[5] J. E. Spurr, "Reconnaissance in Southwestern Alaska in 1898," *U.S. Geol. Surv., Ann. Rept.*, XX, Part VII (1900), p. 190.

[6] Alexander N. Winchell, "Rock Classification on Three Co-ordinates," *Jour. Geol.*, XXI (1913), 214.

[7] F. H. Hatch, *The Petrology of the Igneous Rocks* (London, 1914), p. 195.

[8] F. W. Clarke, "Data of Geochemistry," *U.S. Geol. Surv., Bull. 491* (1911), p. 31.

12 per cent, andesine 59.2 per cent, pyribole 16.8 per cent, mica 3.8 per cent, and other accessories 7.9 per cent.

Syn.: Quartz-diorite.

Dacite STACHE. The name dacite was given by Stache[1] to certain older quartz-trachytes, found in Siebenbürgen (Dacia), which contain oligoclase and pyroxene and which were thus thought to be separated from the younger quartz-trachytes or rhyolites which contain sanidine and biotite. The term has been variously used by different petrographers, some applying it only to extrusive plagioclase rocks with quartz phenocrysts, others including rocks whose only quartz is in the groundmass; some requiring the presence of pyroxene, others including rocks with biotite. In general the name has come to mean quartz-andesite, the extrusive equivalent of quartz-diorite, and it is so used here.

Syn.: Quartz-andesite.

(2212) Syenite. The name syenite was used at least as long ago as the time of Pliny,[2] and was apparently in common use in his day for the rocks from Syene (Assuan), Egypt. "Circa Syenen vero Thebaidis Syenites," he says, "que ante pyrrhopoecilon vocabant," that is, spotted with red. Werner[3] applied the term Sienit to the hornblende-bearing rock from near Dresden, under the impression that the two were the same. It was later found that the Syene rock contains quartz, is, in fact, hornblende-granite, while the Dresden rock is practically quartz-free. Some writers consequently used the term syenite for hornblende-granite, but generally it was used for quartz-free orthoclase rocks in the sense of Werner. Rosière[4] found that the rock of Mount Sinai is of the quartz-free variety and therefore proposed that the name be changed to sinaite. The older term, however, was in such common use that this suggestion was not followed.

[1] G. Stache, "Quarztrachyte Siebenbürgens," in Fr. von Hauer and G. Stache, *Geologie Siebenbürgens* (1863), pp. 56, 70, 79.

[2] C. Plinii Secundi *Naturalis historiae* xxxvi. cap. viii. In the edition Lugd. Batav. Roterodami, Ao. 1668, p. 647.

[3] "Vermischten Nachrichten," *Bergmännisches Journal*, II (1788), 824.

[4] J. F. d'Aubuisson de Voisins, *Traité de géognosie* (Strasbourg et Paris, 1819), p. 21.

There are many varieties of syenite, depending upon the character of the dark or accessory constituents.

Biotite syenite.

Syn.: Syenitite LOEWINSON-LESSING,[1] analogous to granitite for biotite-granite. Polenov,[2] however, had previously used the term in a different sense, namely for syenite-aplite.

Hornblende-syenite.

Arfvedsonite-syenite.

Augite-syenite.

Epidote-syenite.

Pyroxene-syenite.

Hypersthene-syenite (Syn.: Mangerite), etc.

Trachyte HAÜY. The term trachyte, from the Greek *τραχύς*, on account of the rough appearance of the rock, was introduced by Haüy[3] in his lectures at the Jardin des Plantes to characterize the rocks from the Drachenfels on the Rhine. Although the feldspar in these rocks had previously been determined and named sanidine by Nose,[4] yet plagioclase rocks of the general appearance of the original trachyte came to be included in the term. Later, von Buch[5] separated certain Andean extrusives with plagioclase from this group and called them andesites. At the present time trachyte is used for the extrusive equivalents of syenite, that is, for rocks consisting of potash-feldspar, a little plagioclase, and a biopyribole. Many trachytes are orthotrachytes (2111).

(2213) Monzonite DE LAPPARENT-BRÖGGER. The principal rock of Monzoni, in the Tyrol, is of quite variable character. It

[1] F. Loewinson-Lessing, "Kritische Beiträge zur Systematik der Eruptivgesteine, II," *Tscherm. Min. Petr. Mitth.*, XIX (1900), 173.

[2] B. Polenov, "Die massigen Gesteine von nordlichen Theile des Witim-Plateau," *Travaux de la Société Impériale des Naturalistes de St. Pétersbourg*, XXVII (1899), livr. 5, 464.

[3] Haüy did not publish the name until 1822 in his *Traité de minéralogie* (2d ed.; Paris, 1822), IV, 579, but it was accredited to him as far back as 1813 in Alexandre Brongniart's "Essai d'une classification minéralogique des roches mélangées," *Jour. d. Mines*, XXXIV (1813), 43.

[4] K. W. Nose, *Orographische Briefe*, I, 26, 113.

[5] Leopold von Buch, "Ueber Erhebungscratere und Vulcane" (read in Berlin Akad., March 26, 1835), *Pogg. Ann.*, XXXVII (1836), 190.

was called Monzon-syenit by von Buch,[1] and later monzonit by De Lapparent.[2] The latter term served as a collective name for some years, but in 1881 Reyer[3] used it as a specific name for rocks of the Monzoni type, which he thought to be augite-syenite. Earlier Tschermak[4] had recognized the principal rock to be an orthoclase-plagioclase rock, but he applied the term monzonite to the whole series. Lemberg[5] characterized the rock as intermediate between syenite and diorite. In those days rocks were classified either as syenites or diorites, and it was not until 1895 that an intermediate family was established. In that year Brögger[6] introduced the monzonite family. He says: "Es ist . . . . nach meiner Ansicht nothwendig, zwischen den Orthoklasgesteinen und den Plagioklasgesteinen . . . . eine Übergangsordnung von Alkalifeldspath-Kalknatronfeldspath-Gesteinen einzuschieben." The plagioclase of the Monzoni rocks, according to Brögger, is generally andesine to labradorite, or even anorthite.[7] Rosenbusch[8] says that andesine is much rarer in all monzonites than more basic plagioclase, and more acid plagioclase than andesine had not been observed by him in the rocks of Monzoni. Elsewhere, it would seem, orthoclase-acid-plagioclase rocks are more common than those with basic plagioclase. In this classification, therefore, the more acid rocks, that is, those whose feldspar is oligoclase or andesine (sodimonzonites), will be considered normal monzonites, while those with labradorite or bytownite will be included under the calcimonzonites (2313).

[1] Leopold von Buch, "Ueber geognostische Erscheinungen im Fassathale," *v. Leonh. Mineralogisches Taschenbuch für das Jahr 1824*, p. 347.

[2] M. de Lapparent, "La constitution géologique du Tyrol, méridional," *Ann. d. Mines*, 6 sér., VI (1864), 259.

[3] Ed. Reyer, "Predazzo," *Jahrb. d. k. k. geol. Reichsanst.*, XXXI (1881), 36.

[4] Gustav Tschermak, *Die Porphyrgesteine Österreichs* (1869), p. 110.

[5] J. Lemberg, "Über die Contactbildungen bei Predazzo," *Zeitschr. d. d. geol. Gesell.*, XXIV (1872), 188, 190.

[6] W. C. Brögger, *Die Eruptivgesteine des Kristianiagebietes. II: Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol* (Kristiania, 1895), pp. 22–23.

[7] *Op. cit.*, p. 54.

[8] H. Rosenbusch, *Elemente der Gesteinslehre* (Stuttgart, 1898), p. 108; also *Mikroskopische Physiographie der massigen Gesteine* (Stuttgart, 1907), II[1], 167.

Certain intrusive rocks in Banat, cutting through limestones and crystalline schists, were named banatites by von Cotta.[1] They are usually quartz-bearing, and are intermediate between quartz-diorites, quartz-augite-diorites, diorites, and augite-diorites. Brögger[2] applied the name to quartz-bearing monzonites, intermediate between normal monzonites and adamellites, and related to monzonites as quartz-syenites are to syenites. The extrusive equivalent of banatite Brögger is quartz-trachyte-andesite Brögger[3] (see note under 229).

Olivine-monzonite. While the Monzoni olivine-monzonites carry basic plagioclase, elsewhere olivine-monzonites with andesine are found. These rocks, therefore, fall in the present subfamily. Kentallenite is stated by Hatch[4] to be "identical with Brögger's olivine-monzonite. . . . . The two feldspars are present in roughly equal proportions." As a matter of fact, Hill and Kynaston[5] distinctly state that "the term (monzonite) has come to be associated with the presence of an approximately equal amount of the two feldspars—a feature which cannot be said to be an essential characteristic of our group." From the variation in the various specimens described, it would seem that kentallenite is an olivine-orthoclase-plagioclase rock, the ratio of the feldspars being quite variable, consequently not limited to Family 13 here.

Latite Ransom. The name latite, from the occurrence of such rocks in the Italian province of Latium, was used by Ransom[6] for the extrusive equivalents of the monzonites.

Syn.: Trachyte-andesite. (The term trachy-andesite has been used in a different sense from trachyte-andesite by some writers, though others make it synonymous. Rosenbusch[7] uses

[1] B. von Cotta, *Erzlagerstätten im Banat und in Serbien* (Wien, 1864).

[2] W. C. Brögger, *op. cit.* (II, 1895), p. 61. [3] *Ibid.*, p. 60.

[4] F. H. Hatch, *The Petrology of the Igneous Rocks* (London, 1914), pp. 206–7.

[5] J. B. Hill and H. Kynaston, "On Kentallenite and Its Relation to Other Igneous Rocks in Argyllshire," *Quart. Jour. Geol. Soc.*, LVI (London, 1900), 532.

[6] F. Leslie Ransome, "Some Lava Flows of the Western Slope of the Sierra Nevada, California," *Amer. Jour. Sci.*, V (1898), 372.

[7] H. Rosenbusch, *Mikroskopische Physiographie der massigen Gesteine* (Stuttgart, 1908), II, 1036–37.

it, by analogy to trachydolerite, for an extrusive rock whose deep-seated equivalent would be intermediate between alkali-syenite and essexite. It represents, consequently, a rock carrying a feldspathoid or aegirite, riebeckite, etc., and not, as one would suppose from the name, a rock intermediate between trachyte and andesite.)

(2214) **Monzodiorite.** The term syenodiorite was proposed by the writer[1] for the quartz-free equivalent of granodiorite. For the reasons stated under granodiorite (229), this term is withdrawn and monzodiorite is substituted for it.

Syn.: Syenite-diorite BRÖGGER.[2]

Andelatite. For the extrusive equivalent of monzodiorite, the term andelatite, as intermediate between andesite and latite, is suggested. See note under granodiorite (229).

Mugearite HARKER. Mugearite, from the village of Mugeary, is the name given by Harker[3] to certain extrusive rocks resembling basalt but with oligoclase (Ab_7An_2) and much olivine. A modal analysis shows the rock to consist of oligoclase $57\frac{1}{2}$ per cent, orthoclase $12\frac{1}{2}$ per cent, olivine, iron ore, and augite (augite quite subordinate to olivine) $26\frac{1}{2}$ per cent, and apatite $3\frac{1}{2}$ per cent. It is therefore an olivine andelatite.

(2215) Diorite HAÜY. The term diorite (from διορίζω, "distinct") was introduced by Haüy[4] as a substitute for Werner's term *Grünstein*. The name now stands for a rock consisting of acid plagioclase and a dark mineral.

Syn.: Grünstein WERNER, Diabase BRONGNIART.

Oligoclase-diorite.

Andesine-diorite.

Andesite VON BUCH. Formerly there were included, under the name trachyte, not only orthoclase rocks, but those

[1] Albert Johannsen, "Suggestions for a Quantitative Mineralogical Classification of Igneous Rocks," *Jour. Geol.*, XXV (1917), 89.

[2] W. C. Brögger, "Die Mineralien der Syenitpegmatitgänge der südnorwegischen Augit- und Nephelinsyenite," Part I, *Zeit. f. Kryst.*, XVI (1890), 49.

[3] Alfred Harker, "The Tertiary Igneous Rocks of Skye," *Geol. Surv. Mem.* (1904), p. 265; John S. Flett, "On the Mugearites," *Summary of Progress, Geol. Surv.* (1907), p. 119.

[4] The term first appeared in the publications of some of Haüy's students. Thus see J. F. d'Aubisson de Voisins, *Traité de géognosie* (Strasbourg and Paris, 1819), p. 146. Later it was used in Abbé Haüy's *Traité de minéralogie* (Paris, 1822), IV, 540.

containing plagioclase as well. See note under trachyte (2212). In 1835 von Buch[1] described certain volcanic rocks from the Andes, consisting of plagioclase (originally thought to be albite) and hornblende. He named them andesites. Later the term was applied to oligoclase- or andesine-bearing rocks, and it is used in this sense here. The dark mineral may be biotite, hornblende, or augite, or combinations of these, which thus give subfamilies.

Biotite-andesite.

Mica-andesite.

Hornblende-andesite.

Syn.: Hungarite LANG,[2] named from their wide distribution in Hungary.

Augite-andesite. See note under basalt (2315).

Hypersthene-andesite BECKE.[3]

Syn.: Santorinite BECKE. Becke[4] proposed the term santorinite for acid- and alboranite for basic rocks of Santorin. The former are hypersthene-andesites rich in soda (Na:Ca>2). The phenocrysts are labradorite with mantles of oligoclase, while the groundmass is acid oligoclase. The average feldspar, therefore, is acidic. Washington[5] had previously called the acid rocks pyroxene-andesites and had proposed the term santorinite for the members carrying basic plagioclase. Santorinite, used with two meanings, should therefore be abandoned.

(2217) Nephelite- (leucite-) bearing syenite.

(2218) Nephelite- (leucite-) bearing monzonite.

(2219) Nephelite- (leucite-) bearing monzodiorite.

(2220) Nephelite- (leucite-) bearing diorite.

(2222) Nephelite-syenite ROSENBUSCH. Rosenbusch[6] included,

[1] Leopold von Buch, "Ueber Erhebungscratere und Vulcane" (read in Berlin Akad., March 26, 1835), *Pogg. Ann.*, XXXVII (1836), 190.

[2] Heinr. Otto Lang, *Grundriss der Gesteinskunde* (Leipzig, 1877), p. 196.

[3] F. Becke, "Der Hypersthen-Andesit der Insel Alboran," *Tscherm. Min. Petr. Mitth.*, XVIII (1899), 553.

[4] *Ibid.*, p. 553.

[5] Henry S. Washington, "Italian Petrological Sketches: V. Summary and Conclusions," *Jour. Geol.*, V (1897), 368.

[6] H. Rosenbusch, *Mikroskopische Physiographie der massigen Gesteine* (1st ed.; Stuttgart, 1877), II, 204.

under the names Eleolith-Syenit and Nephelin-Syenit, rocks which had previously been described as zircon-syenite, foyaite, miascite, and ditroite. If these terms were not acceptable he suggested that all of the rocks of this class be included under foyaite, since the rocks from Mount Foya, in the Serra de Monchique, province of Algarva, Portugal, as originally described by Blum,[1] are most nearly representative of the whole group. The term eleolite has fallen away, more or less, since the age element in mineralogy is no longer considered, and in general, in this country, the rocks have been called nephelite-syenites. Brögger[2] proposed to subdivide the nephelite-syenites into two groups according to texture. For rocks of this composition and with trachytoid texture he used Blum's term foyaite, and for those with granitic texture Zirkel's[3] term ditroite. In the present classification, under the term nephelite-syenite, are included those nephelite-bearing rocks in which orthoclase exceeds acid plagioclase (oligoclase or andesine) in amount. The rocks in which the plagioclase is albite are here called albite-nephelite-syenites (2122), and those which contain no plagioclase, ortho-nephelite-syenites (212).

Foyaite Blum-Brögger.

Ditroite-Zirkel-Brögger.

Syenoid Shand. As an abbreviation for feldspathoid-syenite, Shand[4] used syenoid, and said the term would "imply the presence of nephelite." He further suggested that gabbroid, dioroid, and doleroid might be advantageously coined in the same manner. Syenoid could well be used as a family name to include both nephelite and leucite rocks.

Leucite-syenite.

[1] R. Blum, "Foyait, ein neues Gestein aus Süd-Portugal," *Neues Jahrb.* (1861), p. 426.

[2] W. C. Brögger, *op. cit., Zeitschr. f. Kryst.*, XVI (1890), pp. 39, 125; also *Die Eruptivgesteine des Kristianiagebietes. III: Das Ganggefolge des Laurdalits* (Kristiania, 1898), pp. 164–65.

[3] F. Zirkel, *Lehrbuch der Petrographie* (1st ed.; Bonn, 1866), I, 595. The term is derived from Ditró, in eastern Siebenbürgen, Transylvania.

[4] S. J. Shand, "On Borolanite and Its Associates in Assynt," *Trans. Edinburgh Geol. Soc.*, IX (1910), 377.

(2223) Nephelite-monzonite. Under this name Lacroix[1] described rocks from Madagascar consisting essentially of anorthoclase, basic labradorite, nephelite, titaniferous pyroxene, barkevikite, titaniferous magnetite, and apatite. The mineral proportions are quite variable. To make it conform with the usual monzonite group, the term nephelite-monzonite is here adopted for a nephelite rock of Class 2 with *acid* plagioclase about equal in amount to the other feldspars. The rock described by Lacroix is included under the calci-nephelite-monzonite family.

Nephelite (leucite-)latite. The extrusive equivalent of the preceding.

(2224) **Nephelite-(leucite-)monzodiorite.** A term here suggested for nephelite-(leucite-)bearing rocks comparable to granodiorites among the quartz-bearing.

(2225) **Nephelite-(leucite-)diorite.** A term, analogous to nephelite-syenite, here suggested for nephelite-acid plagioclase rocks. Under this family would fall Adams and Barlow's[2] raglanite, an abnormal rock on account of its large content of corundum, 4.45 per cent. Since it carries only 12 per cent by weight of nephelite, it is also far from the center point.

Nephelite-(leucite-)tephrites and nephelite-(leucite-) basanites belong here in part.

(2229) No plutonic rock has been located in this family, but there is an extrusive, a leucite-tephrite from the Roman Comagmatic region, described by Washington.[3]

(2230) A leucitite from the Roman Comagmatic region, described by Washington,[4] is the only rock yet found here.

[*To be concluded*]

[1] A. Lacroix, "Sur les granites et syénites quartzifères à aegirine, arfvedsonite et aenigmatite de Madagascar," *Comptes Rendus,* CXXX (1900), 1208; also "Sur la province pétrographique de Nord-ouest de Madagascar," *ibid.*, CXXXII (1901), 439.

[2] Frank D. Adams and Alfred E. Barlow, "Geology of the Haliburton and Bancroft Areas, Province of Ontario," *Mem. Geol. Surv. Canada,* No. 6 (1910), p. 314.

[3] Henry S. Washington, "The Roman Comagmatic Region," *Carnegie Publication. No.* 57 (Washington, 1906), p. 73.

[4] *Ibid.*, p. 136.

Reviews

The Environment of Vertebrate Life in the Late Paleozoic of North America; A Paleogeographic Study. By E. C. Case. Carnegie Institution: Washington Publication No. 283, 1919. Pp. 273, figs. 8 and two correlation tables.

This publication will be welcomed by all geologists as a signal contribution to the interpretation of conditions of the late Paleozoic. Dr. Case is well qualified to summarize the conditions surrounding the vertebrates, and to draw conclusions as to the influence of the environment on their development and distribution.

In the first chapter the various methods of attack and the complexity of the factors in any paleogeographic problem are briefly presented. There follows a summary of late Paleozoic rocks in the several provinces of North America. For the most part the descriptions are quotations from other writers and are not intended to present new material. Quite apart from the obvious purpose, this summary will be of great use to the student, gathered as it is from a voluminous literature on the subject. The selections are well made; they are representative of current opinion, to the point, and show no evidence of an attempt on the part of the compiler to prove a point. The full usefulness is slightly impaired, perhaps, by the absence of an index. The accompanying correlation tables differ little from generally accepted views.

Contrary to what might be expected, the author makes no attempt to fix the lower boundary of the Permian. Throughout the work he refers repeatedly to Permo-Carboniferous times in the sense of a transition period between the Pennsylvanian and the closing events of the Paleozoic. He makes a sharp distinction, however, between Permo-Carboniferous *times* and Permo-Carboniferous *conditions*, and emphatically states that these two things are not necessarily coincident. Perhaps the most important deduction reached, together with the dependent conclusions, is that Permo-Carboniferous conditions prevailed in the east, starting with Mid-Conemaugh time, and reached the southwest considerably later. The deposition of red sediments is taken to mark the introduction of important new climatic and physiographic conditions and accompanying changes—Permo-Carboniferous condi-

tions. These conditions spread very slowly from east to west and, therefore, have left a record oblique to stratigraphic lines (see Fig. 1).

The environment of an organism, "the sum total of all its contacts with the external world," determines to a great extent its structural changes and the distribution of its kind. The equable, humid climate and topographic uniformity of the typical (lower) Pennsylvanian produced an abundant though fixed food supply—vegetation. Since new forms arise only through isolation (not necessarily geographic isolation) the monotony of this environment acted as a repressive force, checking the expansion of the amphibians and reptiles into new forms. "Environmental monotony would result in the persistence of older and simpler types, because the variants, possibly being constantly produced, would not have a chance to develop."

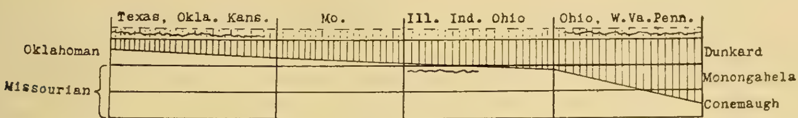

FIG. 1.—"Diagram illustrating in a schematic way the relative position of the sediments formed under Permo-Carboniferous conditions. The land was rising from east to west, but there was continuous sedimentation in the eastern region at the western edge of the rising land of Appalachia. As the land rose slowly the red beds spread toward the west, occupying relatively higher positions in the stratigraphic column. It is difficult to illustrate the actual conditions in the diagram, because the 'red beds conditions' were advancing, but the wavy lines indicate the surface of the ground relative to these conditions. In Pennsylvania and West Virginia deposition was continuous during the conditions. In Illinois and Indiana deposition had ceased by the time the conditions reached that far west; in Kansas, Oklahoma, and Texas 'red-bed conditions' reached the region in time to affect only the uppermost Paleozoic deposits. The upper limit of the red-bed conditions is not known, and so the upper limit of the wedge is indicated by a dotted line" (from Case, p. 192).

Permo-Carboniferous conditions included a cool to cold, arid or semiarid climate, resulting from deformation throughout various parts of the world, the presence of volcanic dust in the air, and a diminution of the carbon-dioxide content of the atmosphere. This made for a great variety in environmental conditions and destroyed the repressive bounds to vertebrate expansion. "The fauna, long restrained from any expression of evolutionary tendencies, full fed, and in the vigor of its youth, responded at once to the change, and new forms appeared so suddenly as to be unheralded in the preserved remains."

These new forms appeared at higher and higher horizons as the Permo-Carboniferous conditions spread slowly westward and "to correlate widely separated groups of beds as synchronous in deposition because of a similarity, even approaching identity, in the fauna or flora would be a serious error."

M. G. M.

Upper Cretaceous Floras of the Eastern Gulf Region in Tennessee. Mississippi, Alabama, and Georgia. By E. W. Berry. U.S. Geological Survey, Professional Paper 112, 1919. Pp. 177, pls. 33, figs. 12.

Another publication is added to the already considerable list which is making fossil plants such an important part of our geological knowledge of the southeastern United States.

The Upper Cretaceous of the eastern Gulf region extends in a lunate outcrop around the southern end of the Appalachians. It is subdivided into the Tuscaloosa formation, the Eutaw formation, the Selma chalk, and the Ripley formation. These formations, with the exception of the Selma, are made up largely of cross-bedded sands, with associated clays.

The most extensive flora is that of the basal Tuscaloosa formation, comprising 151 species of which the majority are dicotyledonous angiosperms. The place of origin of this dominant element is left unsettled, but the idea of their dispersal from an Arctic area is consistent with the evidence offered by this and other Cretaceous floras. This flora is made up largely of lowland coastal types, and its ecological character is in accord with other evidence of the delta origin of the formation. The plants make up an assemblage which most nearly resembles the modern warm-temperate rain forest. In view of their northward range into Greenland, they may be said to indicate a climate mild over wide areas.

The Eutaw flora comprises 43 species, most of which come from the basal portion of the formation and closely resemble those from the Tuscaloosa formation. The physical conditions suggested by this flora are similar to those for the Tuscaloosa.

The Selma chalk, which is described as a lithologic rather than a chronologic unit, is entirely marine and contains no plant remains. The Ripley formation contains a few poorly preserved plant fossils.

The Tuscaloosa formation may be correlated, on the basis of its contained flora, with the upper part of the Raritan and with the Magothy

formations to the north, with the Woodbine sand of southern Texas, and with the Dakota sandstone of the western interior. The Eutaw flora closely resembles the floras of the Black Creek and Magothy formations of the Atlantic Coastal Plain. It cannot be closely related to any of the western floras, but since it is decidedly older than the Montana flora the Eutaw formation may be considered to be synchronous with part of the Dakota and with the Colorado series. The flora of the lower part of the Ripley is related closely to those of the Black Creek, Magothy, Tuscaloosa, and Raritan formations,while that of the upper part shows little relation to any of the earlier Cretaceous floras.

R. W. C.

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Notes on Principles of Oil Accumulation. By A. W. McCoy. Discussed by Chester W. Washburne.

Reply to Discussion by C. W. Washburne on Notes on Principles of Oil Accumulation. By A. W. McCoy.

Diastrophism and the Formative Processes. XII. The Physical States of the Earth and Its Neighbors during Their Formative Stages. By T. C. Chamberlin.

Slides in the Conemaugh Formation near Morgantown, West Virginia. By Earl R. Scheffel.

Factors Producing Columnar Structure in Lavas and Its Occurrence near Melbourne, Australia. By Albert V. G. James.

The Chester Series in Illinois. By Stuart Weller.

The Juan de Fuca Lobe of the Cordilleran Ice Sheet. By J H. Bretz.

A Replacement of Wood by Dolomite. By S. F. Adams.

A Correlation of the Pre-Cambrian Formations of Northern Ontario. By H. C. Cooke.

Pleistocene Mollusca from Indiana and Ohio. By Frank Collins Baker.

The Heart Mountain Overthrust. By D. F. Hewett.

Recent Studies of the Upper Cretaceous of Tennessee. By Bruce Wade.

VOLUME XXVIII NUMBER 3

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COMPILATION AND COMPOSITION OF BITUMINOUS COALS

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A seam or bank of ordinary bituminous coal is readily seen to be stratified; likewise a block or chunk of the same is seen to be highly laminated, and found to be compiled of various layers and sheets of coal differing from one another in color, texture, and fracture, and varying greatly in thickness.[1]

There are generally recognized and described by various authors two kinds of coal with respect to its texture: compact coal and mineral charcoal or mother-of-coal. The former forms by far the larger and the more important part, while the latter forms but a very small, but on account of its nature a conspicuous part of the coal. The mineral charcoal will be considered as unimportant and only incidentally in this paper.

In the compact coal, in general, two kinds of layers are recognizable, apparently alternating and standing in sharp contrast to one another. The one is of a jet-black, pitchy appearance, more compact, and breaking with a concoidal fracture. The other is somewhat grayish in color, of a dull appearance, less compact, and

[1] The figures mentioned in this article are arranged on plates at the end of the article. See Explanation of Plates, p. 206.

breaking with a rather irregular fracture. The former is generally designated as "bright coal" or "glanz coal," and the latter as "dull coal" or "mat coal." On a more careful examination, it is seen that the "bright coal" consists of lenticular masses, greatly varying in breadth and thickness and entirely surrounded by or imbedded in the "dull coal."

It is further found that the "dull coal" is extensively sublaminated into thinner sheets of "bright coal" and "dull coal"; and again on a more minute examination, the bright coal layers are found to be embedded in the dull coal.

The distinction between "bright coal" and "dull coal" has been recognized since the close of the eighteenth century, and many theories have been advanced since that time to explain the phenomenon, but a satisfactory explanation and a true meaning of the alternating dull and bright layers and laminae has never been given.

A condition prevailing generally in all ordinary bituminous coals is well illustrated in Figure 1, representing a small chunk of Illinois coal. In this lump, the "bright coal" is represented by uniform black bands *a*, while "dull coal" is represented by the lighter, finely striated bands *d*. In this respect all ordinary, bituminous coals, no matter from what locality they may be chosen, are similar. Some, of course, like the coal from the Vandalia mine, near Terre Haute, Indiana, possess a larger proportion of "bright coal." Others again, like the coal from the Pittsburgh seam, show a larger proportion of "dull coal"; some seams are all "dull coal," but these are only differences in degree and not in kind.

The sublamination of the "dull coal" is much better illustrated in a vertical fracture slightly magnified, say ten diameters, and especially when such a surface is first smoothed and polished (Fig. 2). The very best illustration, however, is to be had from a thin section, by means of transmitted light and at a low magnification, provided a large enough section is available (Figs. 7 and 10).

Figure 2 represents a part of the surface of the block just shown, limited by the intersecting lines x–x', y–y', m–m', and n–n' and magnified 10 diameters. The bands *a*-1, *a*-3, *a*-5, and *a*-7 represent

"bright coal," and the bands *d*-2, *d*-4, *d*-6, and *d*-8 represent "dull coal." The lettering in Figure 1 and Figure 2 correspond. It may readily be seen that the bands of "dull coal" are compiled of thin black strips which have a black glistening appearance in the coal, interlayered by a lighter-colored matter which has a dull grayish appearance in the coal and is of a rather uniformly granular nature.

All ordinary bituminous coals thus far examined are similar in this respect and any coal might have been chosen equally well to illustrate this condition.

THE "BRIGHT COAL"

Since the term "bright coal" or its equivalent "glanz coal" is applied to a definite component in coal and has become permanently embodied in the literature, the matter must be treated as a separate subject. In speaking of "glanz coal" or "bright coal" it becomes necessary to limit this designation to those bands or components easily recognizable with the unaided eye, such as are designated by *a* in Figures 1 and 2. Such a limitation draws an arbitrary line between the larger bands easily visible and the thinner ones not so easily distinguishable, and comprising a part of the "dull coal" as already indicated. There is no hard-and-fast line between the two. It is with this restriction that the concept of "bright coal' or "glanz coal" is used at this time.

The question that is constantly raised and that must be definitely answered is, "What are the bands of "bright coal" and what is their origin?" In an examination of Figure 1, although representing but a small piece of coal, it will be seen that a number of the bands of "bright coal" taper off on one end. When a larger block is examined many more will be found to do the same and several may be found to taper off on both ends; and when a very large block or a bank of coal is examined closely almost all, if not all, of the bands of "bright coal" are found to taper off on either end. It may be necessary to follow some of the bands for a considerable distance, many feet possibly, but eventually they terminate in a similar manner. Finally when these are examined in all lateral directions, it can be shown that they taper off in all

directions and hence are lenticular bodies and definite components, and are in reality not layers in the strict sense but lenticular masses.

These components vary, of course, greatly in size and form. Their lateral dimensions may range, as already intimated, from a few millimeters to that of many feet; and in shape may range from that of being approximately equilateral, oval, or circular to that of being many times longer than wide. They are all relatively thin, ranging from a thickness barely visible to that of several inches. But strips of a thickness of more than one or two inches are rare and even such of thicknesses approaching one inch are by no means frequent.

"Bright coal" is anthraxylon.—It is not difficult to show that the so-called "bright coal" are components that are derived from the woody parts of plants, parts that at one time were largely composed of wood. Thin sections were cut, both cross-wise and parallel to the bedding planes, from a considerable number of bands of bright coal from a number of different beds and were examined with the view of determining their origin. Every one examined proved to be derived from some woody plant tissue, either of stem, branch, or roots. In every one the cell structure was well-enough preserved so as to leave no doubt as to its origin. "Bright coal" has yet to be found in which no trace of cell structure is observable.

A good example, representing average conditions of the cell structure is shown in Figures 3 and 5. These photographs represent cross-sections of the woody fibers, or, as it is often called, sections across the grain. It will be noticed that the walls have collapsed and are pressed very intimately together, but that the actual mass of the cell walls has retained most of its original matter. There is, however, a considerable variation in this respect in different components and even in the same components, as is shown in Figure 3. In the upper part of this photograph the cell walls have retained most of their original mass, while those shown in the lower part have become thin and in spots poorly definable, a large part of the cell walls having vanished. In some pieces the remaining tissue resembles that of well-preserved sound wood, except that the walls have collapsed; in other cases again the remaining structure is barely recognizable; the whole tissue has

become homogeneous and the lumena and the middle lamella have been effaced. All possible degrees of preservation may be seen between these two extremes.

There can, therefore, be no doubt that the bright coal represents components derived from larger pieces of woody tissues, such as fragments of stems, branches, and roots now compressed and flattened. In some cases these must have been of considerable size. As it is derived from woody tissues (pieces of wood turned into coal) and consists of definite units easily distinguishable from the rest of the coal, it will be called "anthraxylon," from the Greek *anthrax*, coal, and *xylon*, wood. Bright coal then is synonymous with anthraxylon.

THE "DULL COAL"

Having disposed for the present of the "bright coal" or larger anthraxylon components, closer attention may now be given to the so-called "dull coal" in which the "bright coal" appears to be embedded. It has already been shown when seen in cross-section, that it consists mainly of two kinds of material; thin black bands interlayered by a lighter-colored granular-appearing matter (Figs. 1 and 2). The "dull coal" may, therefore, conveniently be divided into two classes: the thin black strips and its embedding matrix, the attritus.

The dull coal as seen in horizontal cleavage surfaces.—When horizontal cleavage surfaces of any compact coal are examined, a varying number of patches showing woody structures are observed to be distributed over the entire surfaces, surrounded more or less by structureless areas (Fig. 4). These patches vary considerably in size, form, and number. But usually they are relatively small and vary within certain limits. This condition is best illustrated in Figure 4, representing a cleavage surface of the coal from the Vandalia mine, near Terre Haute, Indiana. It represents a horizontal fracture through perfectly compact coal and only a very few of the patches seen represent mineral charcoal. Since this coal splits very readily in any desired plane, very many thin sheets may be obtained and thus many horizontal cleavage surfaces may be produced for observation. All reveal appearances very similar

to the one represented. It will be noticed that the woody patches, about one-half natural size in the photograph, are all relatively small and that in many cases the sides running parallel to the direction of the wood fiber form approximately straight lines, while the sides cutting across the fibers are irregular. Rounded and very irregular patches are not uncommon. The condition so clearly expressed in the Vandalia coal is common, in a more or less varying degree, to all the ordinary bituminous coals thus far examined. The example given may, therefore, well serve as a representative type common to all ordinary bituminous coals.

The patches are solid components.—The question at once arises, Are the woody patches, universally seen on the horizontal cleavage surfaces, merely the impressions of some woody fragments that have long since disappeared or are they actual constituents or components of the coal?

It is not difficult to show that the woody patches represent solid masses on the one or the other side of the cleavage surface. There is, however, for each such component a counterpart patch in the corresponding cleavage surface, which is an impression. On cutting with a fine, sharp tool into the patch representing the component, a thin glistening layer of coal is found immediately underneath the surface over the entire patch. Also when a lump of coal is submitted to Schulze's maceration reagent for a certain length of time it may be brought into a condition in which it readily separates into numerous thin, scaly fragments. Many of these bear the woody structure on both sides and when broken show glistening, glassy, jet black coal in the interior. Or, after a treatment for a certain length of time with this reagent, a small lump of coal may be dissected and there may be isolated small sheets or scalelike masses bearing woody marks on the surfaces and consisting of bright glistening coal in the interior.

In splitting a lump of coal it is very rare that the fracture runs through the middle of these thin components, but almost always along one of its surfaces. The larger components of bright coal or larger anthraxylon elements, on the other hand, almost always split through the interior, exposing glistening jetty coal of the same appearance as that in the thin components.

The components seen as patches in the horizontal cleavages and the thin black bands seen in the vertical sections are identical.—The next question arises, "Are the components seen as patches on the horizontal cleavage surfaces as shown in Figure 4 and the black, thin bands seen in cross-sections of the 'dull coal' as shown in Figures 1 and 2, and Figures 7 and 10, identical?" This question can also be definitely answered in the affirmative. A piece of coal, small enough to be placed under a dissecting microscope, may be split horizontally with a sharp tool through any desired lamina; and when thus carefully manipulated it may easily be shown that the black bands seen in the cross-section are the thin, flat components seen on the horizontal cleavage surfaces.

The thin black bands are anthraxylon.—On account of the woody structure present on the surfaces of these components, it must at once be inferred that they are also derived from fragments of woody tissues. The correctness of this inference must be demonstrated so as to leave no doubt.

Correlation of opaque sections with thin sections.—In order to make the demonstration easier and more convincing it is desirable to correlate the appearance of the opaque surfaces of the coal, either at macroscopic observation or at a low magnification in which the characters have already become familiar, with the appearance of thin sections observed by means of transmitted light.

Figure 7 represents the appearance of the cross-section of "dull coal" of an Illinois coal as seen by means of transmitted light at a low magnification. This should be compared with Figure 2, previously referred to, taken from an opaque section of the same sample of coal and at the same magnification, but by means of reflected light. The darker bands in Figure 2, which have been shown to be the components seen as patches on the horizontal cleavage surfaces, correspond to the lighter, more homogeneous-appearing bands interlayered by the heterogenous-appearing laminae shown in Figure 7.

Figure 7 shows numerous strips of thin "bright coal." Figure 8 shows a part of the same at a much higher magnification and plainly shows plant structure in all, but particularly in the strip *a*-1.

Figure 9 is a random horizontal section of coal from the same bed showing that woody structure is present everywhere.

The illustrations given represent the average conditions of most coals in which it is not difficult to detect, in any cross-section, plant structures in most of the strips in question. In some coals, like that from the Vandalia mine and that from Buxton, Iowa, it is not so easy to detect structures so readily in cross-sections. In the horizontal sections, however, plant structures are invariably revealed.

The coal from the Vandalia mine near Terre Haute, Indiana, as shown in Figure 10, at a low magnification is compiled of innumerable thin strips separated by very thin layers of attritus. Cross-sections, at a higher magnification, are shown in Figure 11. The bands *a*-1, *a*-3, and *a*-5 represent some of the thin strips seen in Figure 10. There is very little in these that resembles plant structure. In the horizontal sections, on the contrary, no matter where cut, it is clearly shown that these strips still bear a profusion of plant structure as seen in Figure 12. Of all the coals examined the Vandalia coals contain the poorest preserved structures. Similarly in all coals there are many strips in which at a casual observation no or little direct plant structure is noted, but when such specimens are examined in horizontal sections, plant structure is invariably found to be present. There is, nevertheless direct evidence of such structure almost always observable in cross-sections in the great majority of strips. It will be noticed that most of them have a finely striated or fibrous appearance and this structure is due to the remaining plant structure in the strips. This structure becomes recognizable in the horizontal sections and hence is a direct evidence of cell structure.

A large number of horizontal sections have been prepared from a considerable number of coal seams and in every case cell structure still existed in these thin laminae. The evidence may be considered conclusive.

There exists, therefore, little doubt that the thin bands of bright coal forming a large part, and in many the largest part of the dull coal of ordinary bituminous coals, are also derived from the woody parts of plants. But instead of representing larger parts of plants

they represent only small fragments or chips of the same. The thin strips of "bright coal," therefore, are also anthraxylon components.

Origin of the small anthraxylon components.—It is interesting to know why so large a bulk of the coal should exist in the shape of these thin but relatively wide or broad anthraxylon chips. This question is readily and satisfactorily answered by analogous conditions in peat. Furthermore, a study of these chips of wood in peat lends at once, by analogy, a proof of the woody origin of the anthraxylon components in coal and form a picture as to what may have taken place in the peat bogs of the Coal Age.

In examining a peat deposit such as had its origin in an arboreal growth (Fig. 13), it is discovered that a large proportion of the woody matter consists of thin scaly chips, as shown in Figure 14, which may easily be separated from the peat. As shown in Figure 15, they consist of very thin tangential shells and thin radial plates.

The larger stems and branches of the fallen trees while still above the surface of the deposit become partially decayed. The tissues, having thus become very much weaker along the spring wood of the annual growth rings where the cells are large and the walls relatively thin, are apt to separate along this area, peeling off as thin tangential sheets at the slightest disturbance. A semi-decayed stem of the basswood, Tilia Americana, is a well-known example with a tendency to peel off in this way. Sheets of semi-decayed wood of that nature break up very readily into smaller and still thinner chips. Conifers also have a tendency to peel off in this manner. In trees with broad rays like the oak, the weakest areas are formed along planes parallel to the medullary rays and the tissues will separate into thin radial plates instead of tangential scales or shells. Through either mode of disintegration numerous thin and relatively broad plates or scaly chips of semi-decayed wood are formed. These constitute a very large proportion of the peat. A similar mode of disintegration must have taken place in the peat stage of the Paleozoic coals, as the small anthraxylon chips in coal indicate. The chips in coal and the chips of woody peat in peat are similar.

The kinds of tissues represented in the coals.—In an examination of a considerable number of sections from a number of coals, it is learned that by far the larger proportion of the tissues remaining represent woody parts of plants. By woody parts of plants is meant parts of stems, branches, twigs, and roots, including all the tissues, except the bark, that goes to make up such a part of the tree or shrub. It cannot be said with certainty that the bark has contributed to any extent to the constituents in question. If bark is present at all in coal it finds its recognition possibly in components appearing altogether different, which will be discussed later.

The anthraxylon of the dull coal then is derived for the most part from rather small chips of semi-decayed woody tissues, such as are prevalent in the peat bogs of today. Prosenchyma or wood proper, and parenchyma such as cortex, pith, and rays are all met with and are clearly distinguishable. There is, nevertheless, no doubt that some of the structure seen in thin sections is derived from the more succulent or younger parts of plants as well as from herbaceous plants. Leaf-strands with some of the accompanying tissues, petioles, and other vascular strands are frequently detected. What appear to be delicate tissues of plants are frequently seen. The parenchyma of leaves is rarely observed, yet occasionally structures are seen that could be construed as having been derived from leaf parenchyma, and in some cases certain structures represent without a doubt leaf tissues in which all the leaf tissues, particularly the palisade cells, are well represented, and may be favorably compared with the leaf tissues of a living Cycad. In most cases the tissues contained between leaf cuticles have been disorganized beyond identification. Occasionally tissues are found in a fairly good state of preservation which as yet cannot be correctly classified. In this connection spore walls or sporangia should also be mentioned. Sporangial walls, either singly or in connection with remainders of cones, are a common occurrence in most coals, but particularly abundant in the coal from Buxton, Iowa. Such spore walls are often remarkably well preserved. A considerable amount of the woody tissues as well as other plant tissues have been reduced to a finer state of division, exactly as is

the case today in the peat deposits, and hence are classed with the attrition matter and will be discussed under the attritus.

Cuticles.—The outermost layer of tissues of all leaves, petioles, green parts of young stems, twigs, fruit, and seeds of plants, consists of tabular cells very closely united and uninterrupted except by stomatal pores. This is the epidermis. In some plants it persists with but little change; in others it is thrown off sooner or later and replaced by a layer of cork. Delicate epidermis possesses thin walls; but in a large number of plants with fleshy and tough leaves, the walls are of considerable thickness.

The exposed surface of all epidermal cells are covered with a layer of cutin forming a continuous transparent film or membrane over the entire surface of leaf or stem. This film is called the cuticle. It is present on all leaves, pedicles, green or young stems, twigs, fruits, berries, and sometimes persists on older stems and branches. Often the cuticle is further covered with a waxy and resinous matter. In some cases the amount of such substances is large and assumes commercial importance, as in the wax palm (Ceroxylon andicola) and the bayberry (Myrica cerifera). The waxy coatings may be in the form of coherent layers or incrustations upon the cuticle; in crowded vertical rods, sometimes of considerable length; in very short rods or rounded grains, very much crowded on the leaves of some plants; or in minute grains or minute needles.

The cuticle is very resistant to putrifying organisms and persists under peat-forming conditions after most of the underlying tissues have been disorganized or have disappeared. Cuticles or fragments of cuticles are always present in peat, occasionally in large proportions.

Cuticles in coal.—Similarly in coals a large amount of cuticular matter and some cuticularized tissues have survived and are ever-present constituents, often forming very appreciable proportions of the dull coal (Fig. 16).

In thin sections, under the microscope, the cuticles appear as bright golden-yellow bands of considerable length but relatively narrow. One edge is usually smooth while the other is usually saw-edged. Frequently they are found in pairs with the same-edged

sides toward each other. Figure 17 is taken from a section containing a large proportion of cuticular matter very similar to that shown in Figure 16. Here the cuticles are represented by comparatively heavy light-colored bands, sometimes in pairs embedded in a general débris derived largely from leaves and other vegetable matter. Cuticles are sometimes accompanied by well-preserved leaf tissues. Cuticular matter is also present in a macerated or more or less fragmented condition. When in this condition it forms a constituent of the attritus, and is often difficultly distinguishable from fragmentary spore-exine matter which it closely resembles in color and general appearance.

Like the spore-exines the cuticles may very easily be separated from the coal by means of Schulze's reagent. When thus separated from the coal they appear as tissues or films constructed of cells (Fig. 18). They are, however, non-cellular, hyaline membranes and the apparent cell structure is due to ridges on the under surface that conformed to the once underlying epidermal tissue. In cross-section these ridges give the saw-edged appearance. A considerable number of patterns of the apparent cell structure, or in other words, different types of cuticles, are found, thus indicating that a number of different species or genera of plants are involved.

BARK

It cannot be said with certainty that bark has contributed any appreciable amount to coal; nothing has been met with that could be referred to with certainty as derived from bark. There is, however, a constituent reoccurring in all coals, most frequently in the coal from the Pittsburgh seam, that might be interpreted as being derived from bark. It is shown in Figure 6. This component is always of a dark-brown color, lumpy, porous, and of irregular structure. By far the largest proportion of it has retained some of its original plant or cell structure. On the whole, the remaining cell structure is very poorly and very irregularly preserved and appears to be derived from large-celled tissues. It almost always includes a large number of resinous-appearing globules, and frequently also more highly carbonized matter. It also frequently includes parts of the tissues, or strands of tissues, in which the plant structure is still well preserved. In some of

the components the whole mass is fairly well preserved and then again, components are met with in which the whole mass is disorganized and consists of irregular fragments, but always of the same color and general appearance. Frequently the component is composed of bands of more or less well-preserved tissues alternating with bands of disorganized, granular matter.

The components vary largely in size as seen under the microscope, ranging from but tiny bits to good-sized masses. There is also a wide range of transparency in them, both in different components and in different parts of the same component. The most transparent ones are of a dark-brown color in thin section, but opaque in medium-thick sections.

This component, possibly derived from bark, is characteristic through its brownish red color in thin section, irregular structure, lumpiness, and relative opacity, and is easily distinguishable from the rest of the coal. Although in some layers or laminae it may be quite abundant, yet, on the whole, it forms but a small part of coal.

The attritus.—It has been shown that the larger anthraxylon components or bands of bright coal are embedded in the dull coal; and in turn that the dull coal consists largely of smaller anthraxylon constituents together with a few other constituents such as cuticles and barklike constituents, embedded in a general matrix, the attritus.

At low magnification, the attritus appears as a uniformly granular, amorphous mass (Figs. 2, 7, and 10). At a higher magnification, it at once appears as a very heterogeneous substance. Typical appearances of the attritus in cross-section are shown at *d*-2 and *d*-4 (Fig. 11); at *d*-1, *d*-3, and *d*-7 (Fig. 19); at *d*-1, *d*-3, and *d*-5 (Fig. 20); and in horizontal section in Figures 22, 24, and 25. A close examination at a high magnification will at once reveal that it is composed of a number of groups or classes of constituents, most of the members of which are specifically and definitely definable and their origin determinable. These are cellulosic degradation products or humic matter, spore-exines, resinous matter, cuticular matter, more highly carbonized matter, certain small bodies usually designated as rodlets or needles, and some mineral matter.

The humic matter, or cellulosic degradation products.—In the photographs just referred to, particularly noticeable at *d*-1 (Fig. 19), there will be recognized besides the strips designated as anthraxylon constituents, other strips similar in appearance but thinner and more irregular in width and bearing no marks of plant structure. Besides these, there are other more globular constituents, some of very small sizes, others very finely divided. These are of the same general appearance and color as the anthraxylon matter and constitute part of the attritus. Most of this matter evidently is of the same general origin as the anthraxylon components, and may be collected into one class and designated under the general term of "humic" matter. Under "humic" matter then is considered the cellulosic degradation products in a state of division finer than the smaller anthraxylon components but not including resinous, cuticular, spore, or carbonaceous matters. There is no hard-and-fast line of distinction between the smaller anthraxylon components and the humic matter. The particles constituting the humic matter in general no longer bear visible marks of plant or cell structures and are smaller in sizes.

It should be emphasized that the humic matter consists very largely of definitely definable particles and not of a vague plastic or homogenous mass, and only a comparatively small proportion is so finely divided as to lose its individuality even under very high magnifications. When this stage is reached, we enter the realm of colloidal conditions, and proper methods will here also show that the matter consists of individual particles.

There must be included in the term humic matter, substances of a wider origin than the anthraxylon, such as gums, pectins, cork, bark, and other substances closely allied to the cellulosic materials. In analagous studies of peat, where the constituents are more easily identified, there is very little matter that is of other origin than cellulosic; and if the formation of coal and peat is to be considered analogous, the conclusion must be drawn that but a small proportion of the humic matter in coal can be other than of cellulosic origin. This, however, does not dispose of a long list of substances known to exist in plants, such as tannins, alkaloids, oils, terpenes, camphors, etc.; but if these or their derivatives are still present

it is very likely that they are present in an absorbed condition; that is, absorbed by the anthraxylon and other constituents, and so will have lost their identity under the microscope. In the peats, many of these substances may be detected by microchemical means, and are found to be absorbed mostly by the woody constituents, but ordinarily are not visible under the microscope.

Since there are no, or at the most very few, plant structures remaining in that part of the coal classed under the attritus, the origin of all its constituents, with the exception of the spore-exines, cuticular matter and certain resinous matter, cannot be as closely defined as the anthraxylon matter. Though much of this matter is clearly shown to be woody degradation products, yet it is highly possible that a considerable amount of bark and cortex is included. As has been stated before, bark, that is, that part of the tree or plant usually designated by that term, has not been recognized positively in the coals examined. Cortex, pith, and parenchyma have been recognized comparatively speaking in small quantities. The conifers of the Paleozoic times probably were the only trees with true bark, and the bark of these undoubtedly disintegrated similarly as that of the peat-forming trees and shrubs of the present, and this largely lost its identity and still exists as humic matter.

The spore-exines.—The spore-exines (Figs. 27–41) are ever-present constituents, and no coal is entirely free from them. Even the coals with the least number of spore-exines, like the Vandalia coal from Indiana, contain a considerable amount of spore matter. Under the microscope, in thin section, they are the most conspicuous objects in the coal, due to their clear yellow color and transparency. In the photographs, representing cross-sections, at a magnification of 200 diameters, they may be recognized as very small linear patches (Figs. 19 and 20). At higher magnifications, say at 1,000 diameters (Fig. 21), their true nature is more clearly shown. Here they appear, when whole, as collapsed rings, being in reality collapsed spheres, and merely represent the outer shells or spore walls or exines of once living spores of the Paleozoic plants that evidently also contributed to the coal themselves. Its contents, such as nuclei, protoplasm, chloroplasts, and inner spore

wall have disappeared completely, or almost so. In the photographs at 200 diameters prepared from horizontal sections (Fig. 22), the spore-exines are shown on their broad side, and appear as circular to oval or slightly triangular disks. At a higher magnification, say at 1,000 diameters (Figs. 24 and 25), the characters, such as form, sculpturing, and tetrasporic marks remaining on the exines, are clearly shown.

An excellent way to study the spore-exines is to macerate the coal by means of Schulze's reagent and digest it with ammonia. The spore-exines and cuticles are left undissolved and apparently unchanged. Figures 27–41 show some of the spore exines thus isolated.

From a collective study of all the spores, it is evident that a considerable number of species and genera of plants contributed to the spore matter in coal. Two distinct types of exines are distinguishable. The one is always in the shape of a circular disk, in some cases tending to be triangular and less often tending to be oval or ovoid, and all bear the familiar tetrasporic mark. These are the exines of Paleozoic Pteridophytes. The other is always oval or ovoid, but does not bear the tetrasporic mark and has a long slit parallel to the long axis of the oval; often with a second short slit at, or toward, one of the extremities. The surface is apparently smooth and unsculptured (Figs. 25 and 30). These are undoubtedly the exines of the pollens of certain Paleozoic Gymnosperms.

The exines of true spores.—On the whole, the true spore-exines are much more abundant in coal than are the exines of pollen grains. There is a large range of sizes among them, from that of only about 10 microns (Figs. 22 and 24) or $\frac{1}{100}$ of a millimeter, to that of 2 and 3 millimeters in diameter (Fig. 38). There are to be recognized two kinds: megaspores and microspores. From a biological standpoint, three kinds should be distinguished: megaspores (Figs. 35 and 38), microspores, and neutral spores. This is not only a distinction of size, but also of function. Megaspores in living plants are always large and on germination produce male gametophytes; microspores are always relatively small and produce female gametophytes; while certain other spores, classed among

the smaller ones, may produce gametophytes that may reproduce either male or female gametophytes, there being apparently no predetermination. Among the spores of the coals, no such distinction can be made, and all that can safely be said is that some are large and others are small, and assume that the larger ones are megaspores; but between the spores that functioned as microspores and those that are neutral, no distinction can be made, and the term microspores must apply to both kinds, if used at all. This affords a convenient, if not exact, distinction, between the very large spore-exines and the smaller ones. It should be stated that the range in sizes is gradual from the smallest to the largest, and that no fast line, in regard to size, can be drawn between the two.

The thickness of the exine walls varies very greatly with the kind of spore from which derived, and ranges from the tinest film of only a few microns in thickness to such where it is a huge mass of a hundred microns or more, as in the large megaspores as shown in Figure 38. But the size of the spore is not always commensurate with its thickness. Very large spores are observed with but very thin walls, and again comparatively small exines are met with which have walls equal in thickness to half their diameter.

Almost all spore-exines are sculptured, and only comparatively few are smooth, and each kind has a definite type of sculpturing, which affords a ready means of distinction between them. The sculpturing may take a variety of forms and may consist of serpentine ridges, irregular elevations, echinate protuberances, sharp, slender spines, and short hairlike coverings. In many cases, these are arranged in definite order, as in spirals or rows (Figs. 27–41). Some exines are covered all over with a ramentum; others bear a long tuft of ramentum on a small area only; others have a number of long slender wings; and still others have three large air sacks.

Exines of pollen grains.—A large number of exines present in coals are apparently those of pollen grains (Figs. 25 and 30). In a very large number, especially noticeable when they have been isolated from the coal by means of Schulze's reagent, there is a long slit running parallel to the long axis of the oval; and

frequently with a short cross slit at or near one of the ends of the longitudinal slit, but a tetrasporic mark is never seen. The absence of the tetrasporic mark and the presence of a slit then are characteristic characters. In color, transparency, and consistency they are similar to the true spore-exines. Their surface is always smooth and has no spines, processes, or hairlike coverings. They vary greatly in size, indicating that a considerable number of species or genera of plants are involved. Compare Figures 25 and 30, photographed at the same magnification.

The resinous matter.—There are universally scattered through or contained in the attritus of all coals, certain particles, which, when seen under the microscope, are generally of a more or less rounded or ovoid form, rarely angular or irregular; of a rather homogeneous or vitrious consistency; of a brownish red to red color, a color very similar to that of the anthraxylon components and the humic matter, called resinous particles. Such form a very appreciable part of many coals. These constituents are classed under resinous matter, because they resemble very closely certain constituents in peat and lignite where they are more certainly known to belong to the natural resinous substances of plants. Many of the resinous-appearing bodies in the attritus, moreover, very closely resemble certain bodies still included in the original tissues of both the smaller and the larger anthraxylon components. Further, there are clear cases of transition from where they are still included in the original tissues to that where they are free in the attritus.

There is, therefore, enough basis for assuming that the constituents in question are derived from the natural resins of the Paleozoic plants. The proof is, nevertheless, not as positive as one would like to have it. But since the constituents in question stand in quite sharp contrast to the other constituents and are tolerably well definable into a distinct class of components, the term applied to them is believed to be justifiable. Besides, it affords a convenient means to distinguish them from the other constituents.

Good illustrations of resinous matter in the attritus are given in Figures 23 and 26, also in Figure 19. Figure 26 shows

exceptionally large amounts of it, but layers with equal amounts are not rare in any coal.

The carbonaceous matter.—All ordinary bituminous coals contain certain constituents that are more highly carbonized than the rest of the coal and to which it stands out in sharp contrast on account of their opaqueness. These are well represented in Figure 22, in which these constituents are represented by the more or less irregular black areas. They are also seen in Figures 19 and 20, 21, 24, and 25.

In general, there are two types of carbonaceous matters: one shows definite plant structure and is clearly shown to be more highly carbonized parts of plant cells or bits of woody or other plant tissues, and the other shows no plant structure and is of indefinite origin.

The former usually have retained the original plant form and characters, such as pores, pits, trabacular and spiral thickenings. These are nothing more or less than smaller bits of mineral charcoal. The different constituents of this class of carbonized matter vary largely in the degree of carbonization and hence also in opaqueness. Its opaqueness varies from that where it is only slightly more opaque than the normal anthraxylon constituents to that where it is entirely opaque even in the thinnest sections. In general, however, most of it is opaque in the medium thin sections, becoming translucent in the thinner sections. Relatively very few appear to be entirely opaque in the thinnest sections. When translucent or transparent, they are of a dark-red color, becoming darker with increase of opaqueness and of a lighter red with decreasing opaqueness, approaching a pale yellowish red in color.

The disorganized opaque matter.—The other kind, the disorganized and more irregular kind of opaque matter, is not so easily defined. Its origin is possibly varied, but most of it is of undoubted organic origin. The shape of most of the particles comprising the matter is irregular, but a considerable number are oval to spherical. In size they vary from the most minute particle to that visible to the naked eye. The more spherical and oval particles suggest carbonized resinous matters.

Rodlets.—Other constituents that are invariably present in all coals are the so-called rodlets. Generally speaking, they form

but a small part of any coal, but they are much talked about on account of their conspicuousness and prominence in the mineral charcoal and on the cleavage surfaces. They are called rodlets because they have the appearance of minute rods. By some they are also called needles, because of their slender needle-like appearance. In cross-section, the rodlets appear as circular to oval disks of a dark color in very thin sections; in thicker sections they are opaque. They are of a relatively large size when compared with spores and pollen grains.

Many of the rodlets are scattered helter-skelter through the attritus (Fig. 43). In some laminae they are present in large numbers, and in such cases, form a large proportion of the coal. Many of the anthraxylon components (Fig. 44), and, conspicuously, many of the mineral charcoal constituents, inclose many rodlets that are evidently part of their structure or tissue. Some of the tissues in coal with which rodlets are associated may be classified with the Medullosae (Fig. 44), well-known Paleozoic plants allied to the Gymnosperms. The cortex of the Medullosae is known to have been pervaded by gum or mucilage canals. In a specimen at hand of Medulosa Anglica (Fig. 42), these canals are still filled with a dark solid substance. These solids resemble very closely certain rodlets embedded in the attritus, as well as those associated with anthraxylon components.

The rodlets are non-resinous, give off a blue non-sooty smoke on burning, do not swell or puff up, and do not become viscous when heated. They are of a black, glistening, glassy consistency, breaking with a decided concoidal fracture. When burned, they leave a very delicate, finely grained skeleton of quarts, the relative amount of which varies very largely in different rodlets. In some it forms a very delicate skeleton, while in others there remains a solid mass almost as compact as was the rodlet before burning, except that it is now snowy white. Between these two extremes, all possible intergrades may be observed. In fact, some rodlets consist of almost pure white quartz. Some have a core of quartz surrounded by a shell of black matter.

It seems clear then that some of the rodlets, if not all, are the semi-petrified or petrified contents of the mucilage canals of certain Cycadofilicales, like Medullosa.

SUMMARY

The bituminous coals consist of alternate layers of "bright" coal and "dull" coal. The "bright" coal is called anthraxylon.

The "bright" coal was formed from the large limbs and trunks of trees or parts of them which were not disintegrated in the peat swamps previous to the formation of the coal. This "bright" coal retains its original woody structure, although often somewhat distorted.

The "dull" coal consists of numerous small layers or chips of "bright" coal embedded in a dull matrix, the attritus. These small chips of anthraxylon are derived from the chips, splinters, small stems and branches, twigs, roots, etc. Possibly part of the large woody chunks slightly disintegrated, due to the incipient decay previous to the formation of the coal, and thus provided some of the small layers of "bright" coal. No bark entered into the formation of the small layers of anthraxylon.

The dull matrix or attritus, in which the small layers of "bright" coal are embedded in the "dull" coal, was derived from the following sources:

a) The waxy cuticle covering of the leaves. This is an extremely resistant substance and remains in the coal in narrow, yellowish, semi-transparent bands of varying lengths.

b) Spore-exines. These vary from 0.01 mm. to 3 mm. in cross-section.

c) Pollen exines.

d) Resinous matter. This is the original resinous substance of plants.

e) Small particles of resinous and woody matter from a highly carbonized state down to a little carbonized state.

f) Small rodlets or needles. These are possibly the petrified or semi-petrified gum or mucilage canals that pervaded the cortex of some Paleozoic plants. On burning, they leave a white quartz skeleton.

g) Small amounts of gums, pectins, and corks.

The tannins, terpenes, alkaloids, etc., if still present, are absorbed in the coal and do not show up microscopically.

EXPLANATION OF PLATES

PLATE III

FIG. 1.—A block of Illinois coal from vein No. 6. The black bands *a* represent anthraxylon, the grayish bands *d* represent the layers of "dull coal." The area described by the intersections of the lines x–x', y–y' and n–n, m–m' is the same area shown in Figure 2, and bands *a*-1, *d*-2, *a*-3, *d*-4, *a*-5, *d*-6, *a*-7, and *d*-8 of the one are correspondent to the other. The lenticular band "CO" represents a cone of Lepidodendron. Natural size.

PLATE IV

FIG. 2.—The area described by the lines x–x', y–y' and n–n', m–m' in the block of coal shown in Figure 1, and enlarged 10 times. The bands *a*-1, *d*-2, *d*-4, *a*-5, *d*-6, *a*-7, and *d*-8, representing alternate layers of anthraxylon and "dull coal," of the one being correspondent to the other. ×10.

PLATE V

FIG. 3.—A part of a thin cross-section of "bright coal," or anthraxylon, showing more or less well-preserved structure of wood. ×200.

FIG. 4.—A horizontal cleavage surface of compact coal from the Vandalia mine near Terre Haute, Indiana, showing patches with woody structure or anthraxylon chips, more or less surrounded by structureless areas representing the attritus. "Needles" are also shown. ×200.

FIG. 5.—A part of a thin cross-section of "bright coal," or anthraxylon, with resinous inclusions. ×200.

FIG. 6.—Part of a thin cross-section of coal from the Pittsburgh seam, consisting of a constituent that may be bark. The tissue is large-celled, irregularly preserved, including a considerable amount of resinous matter. ×200.

PLATE VI

FIG. 7.—Part of a thin cross-section of coal from Royalton, Illinois, at a low magnification, showing numerous thin chips of anthraxylon, more or less separated by thin layers of attritus. × 10.

FIG. 8.—A part of the thin section shown in Figure 1, at a higher magnification. Some of the anthraxylon chips have retained their cell structure to a remarkable degree, a common occurrence in most coals. × 200.

FIG. 9.—A part of a thin horizontal section of the coal from Ziegler, Illinois. A random section; the plant structure shown is of common occurrence in any horizontal section. Anthraxylon chips are seen on either side. The circular to oval spots in the attritus in the center represent spore-exines. × 150.

FIG. 10.—Part of a thin cross-section of the coal from Terre Haute, Indiana, at a low magnification. The numerous grayish bands or strips represent anthraxylon chips; the darker mottled matter between these represents the attritus. × 10.

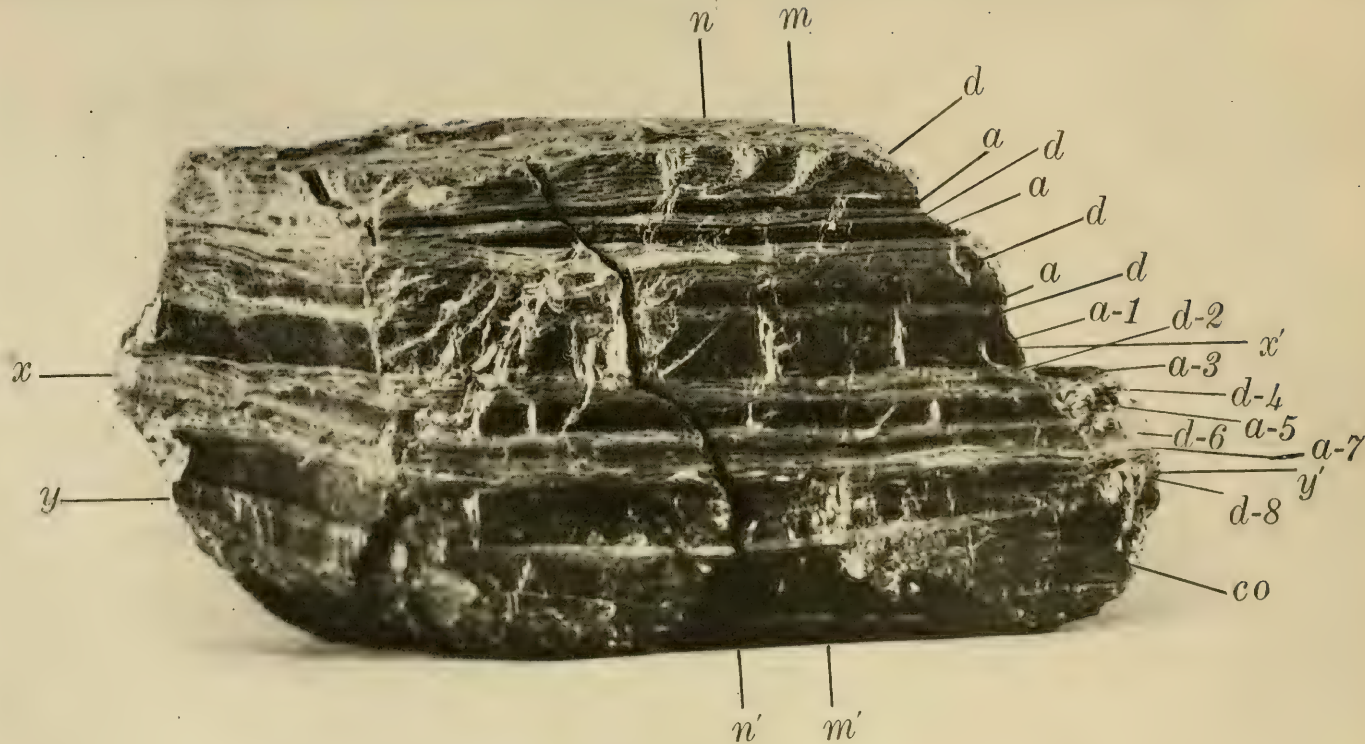


FIG. 1

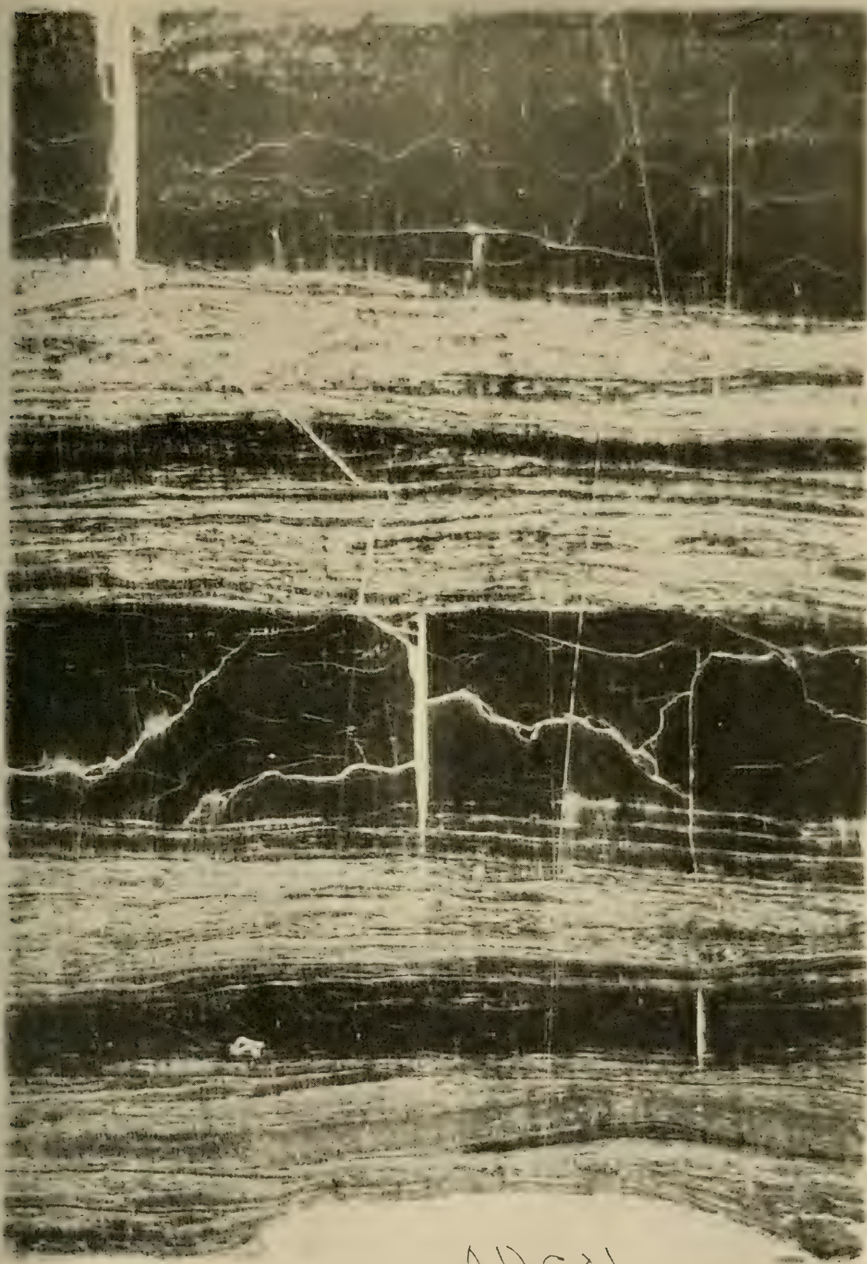
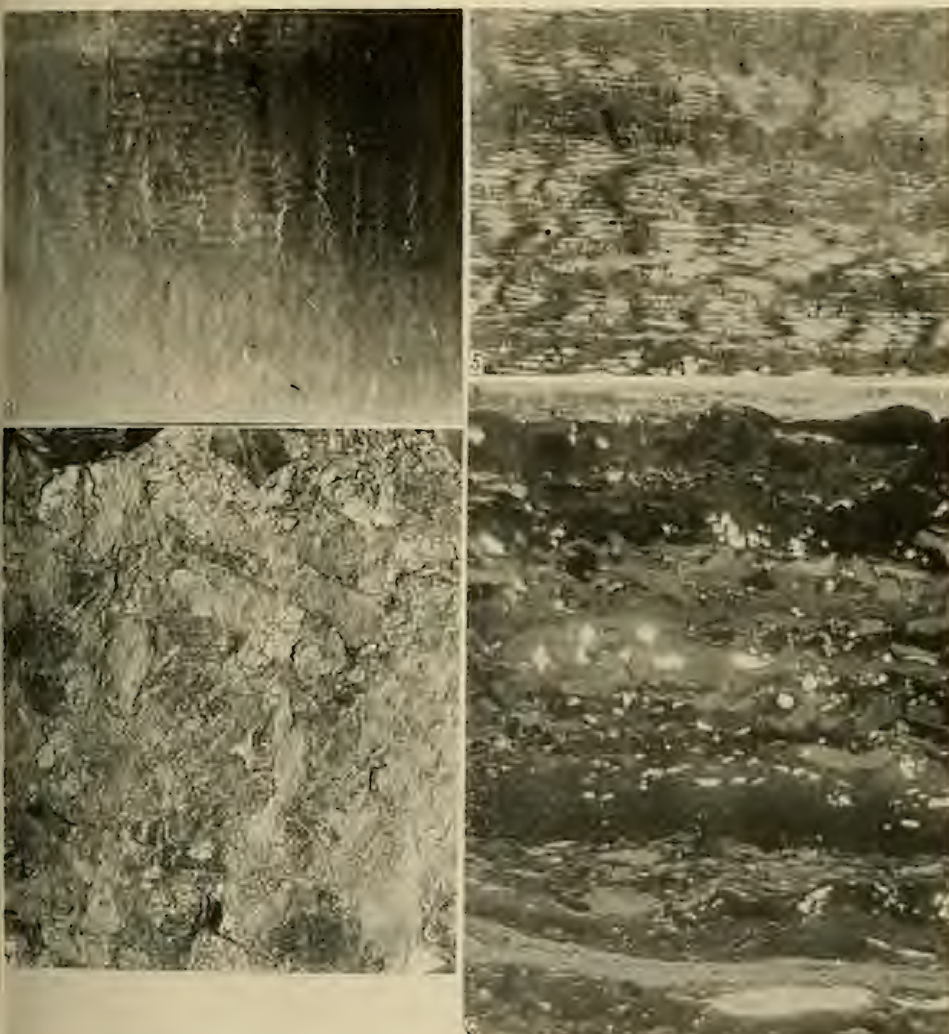
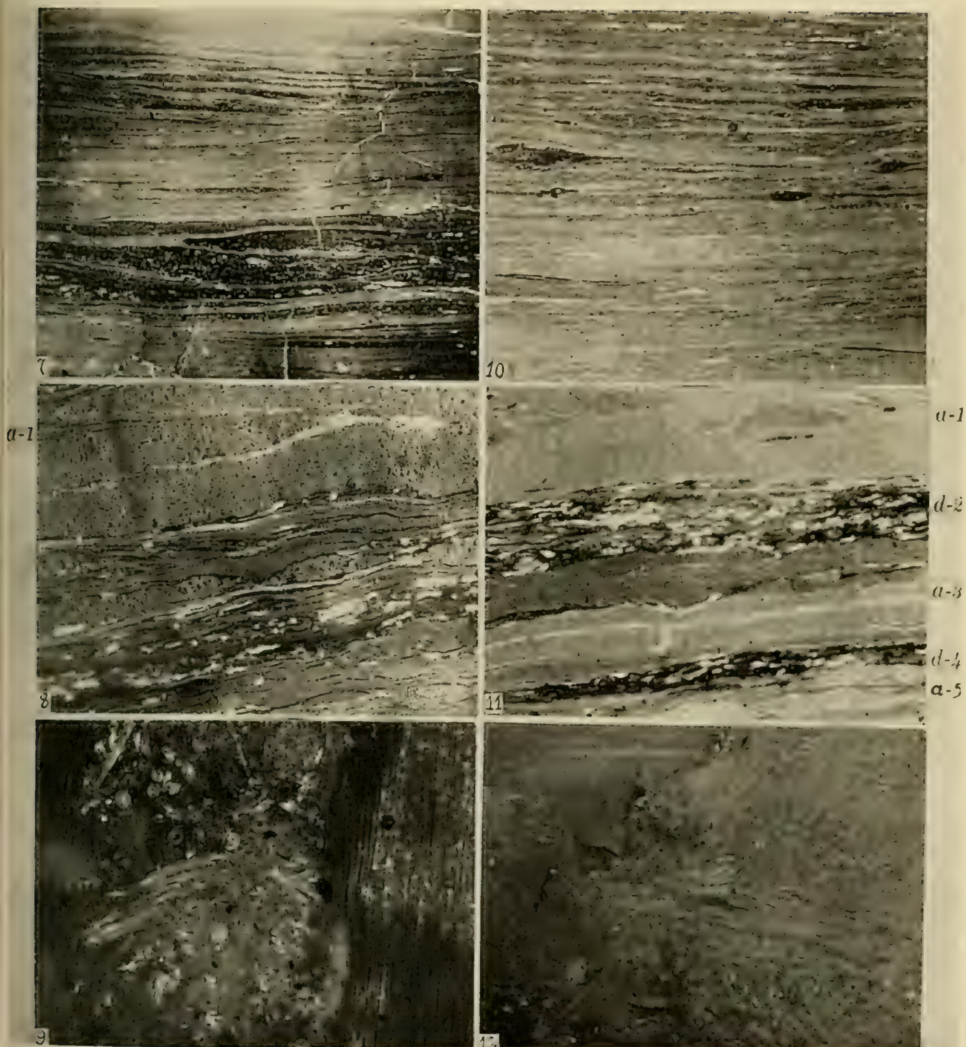


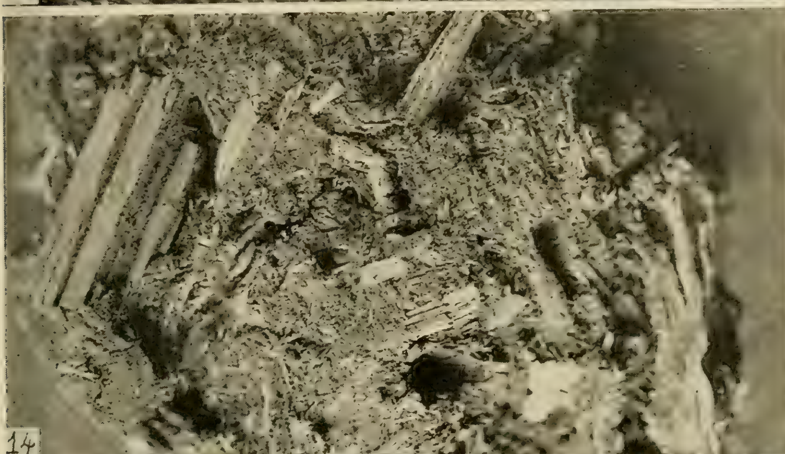
Fig. 2



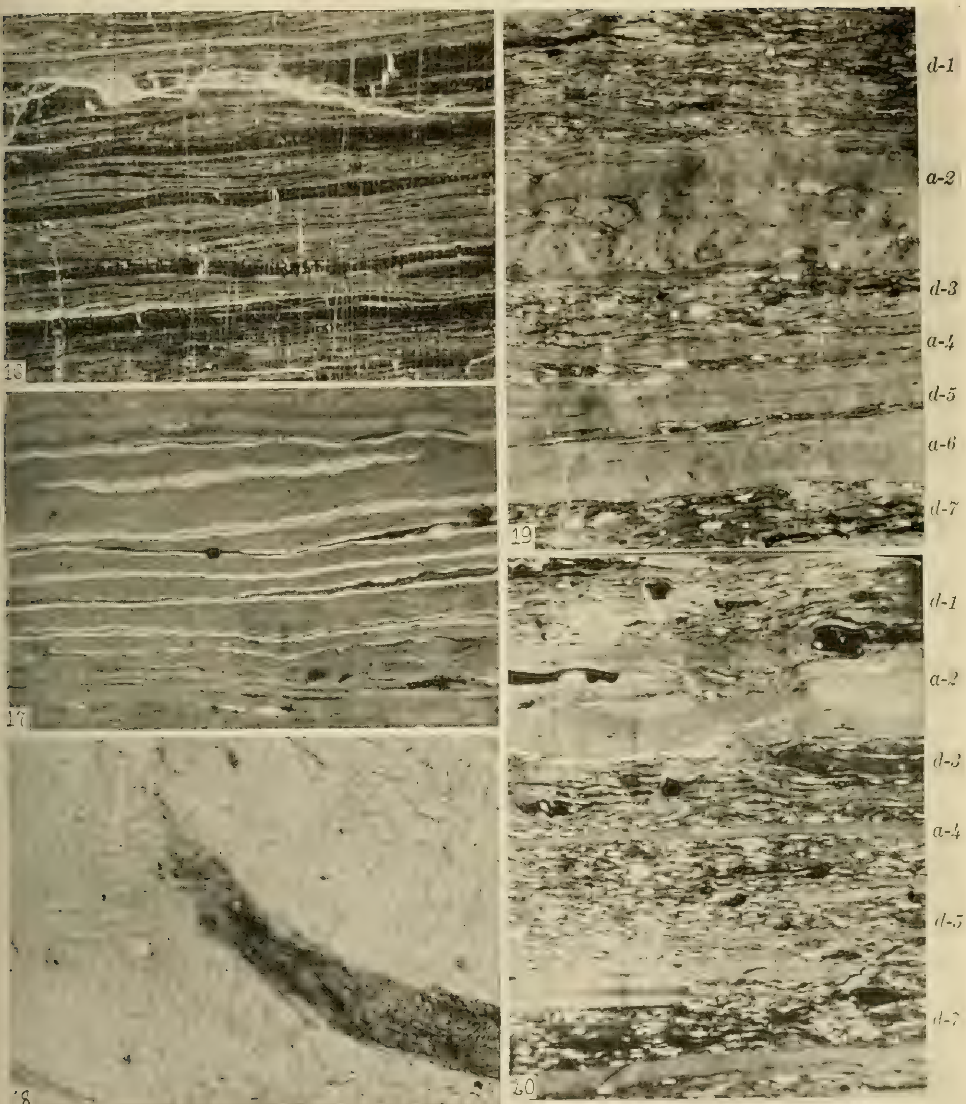
Figs. 3–6



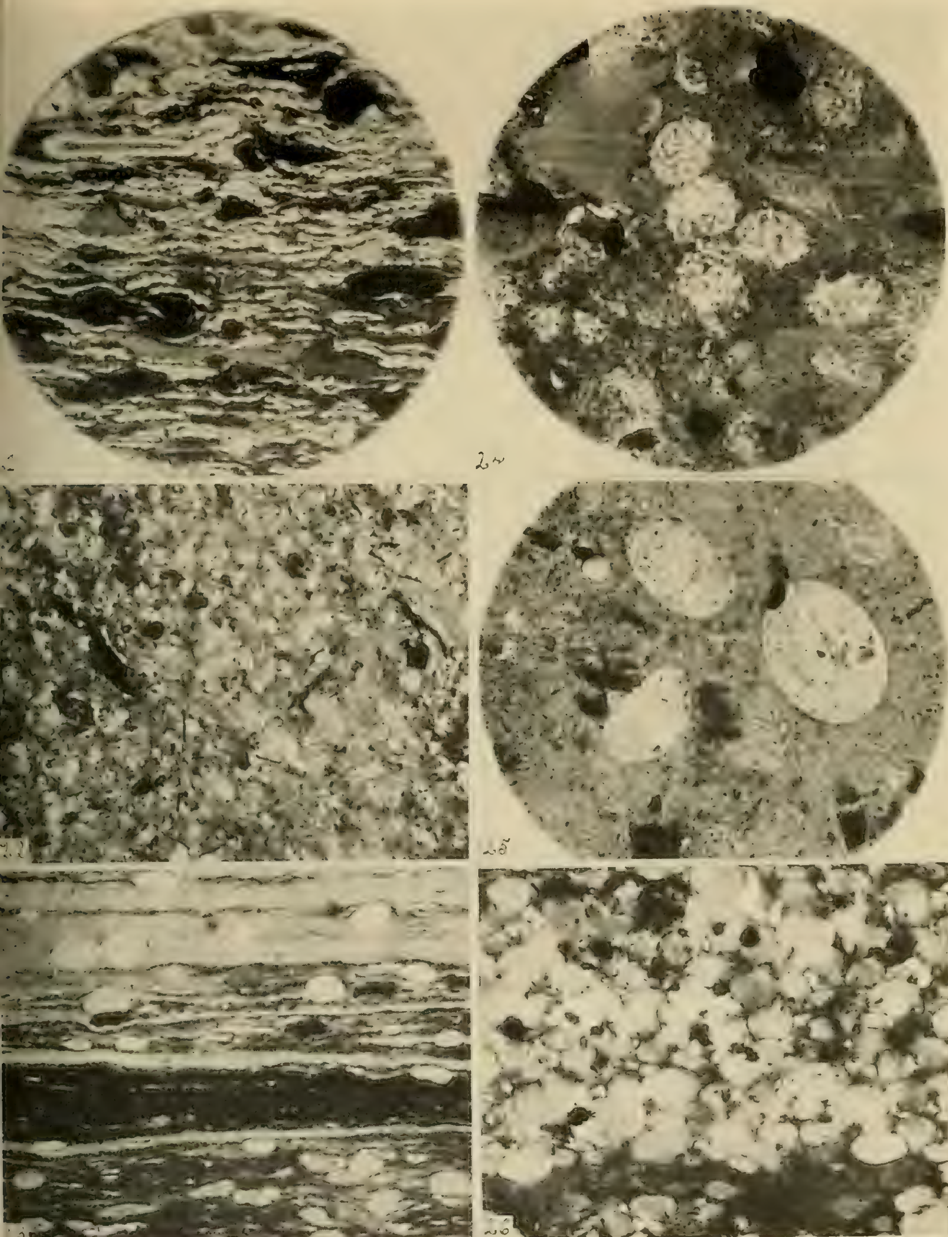
Figs. 7–12



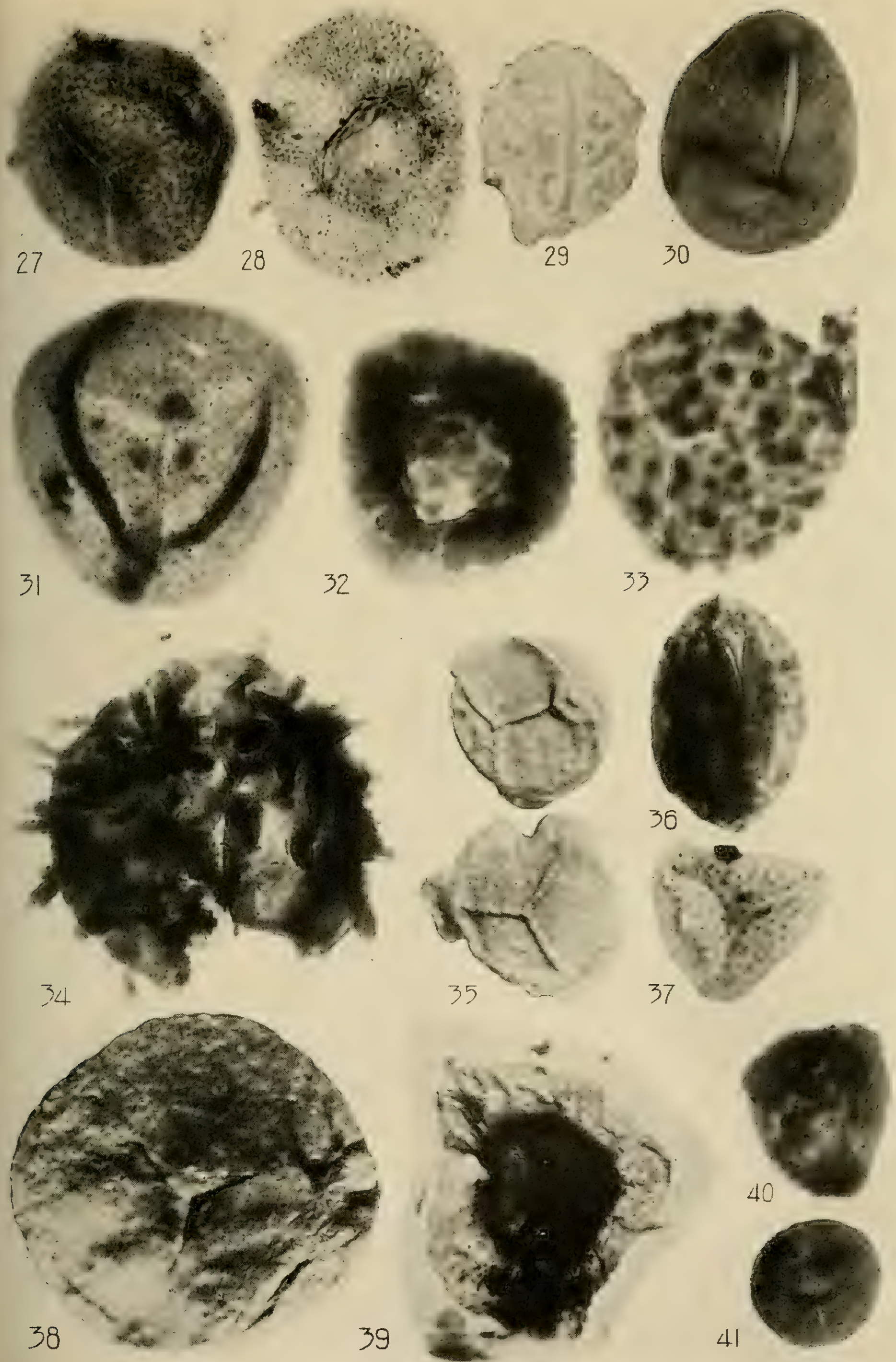
FIGS. 13–15



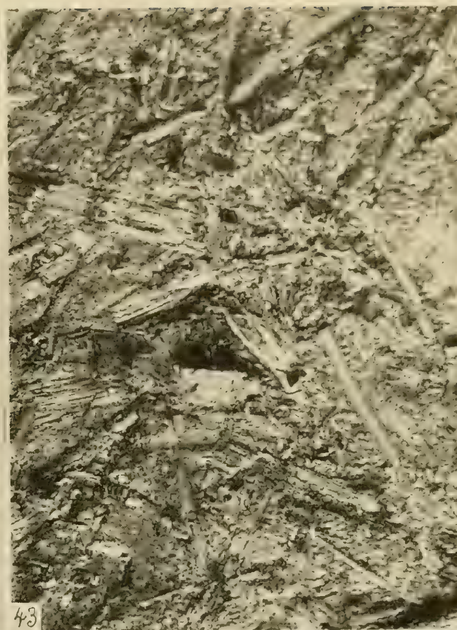
Figs. 16–20

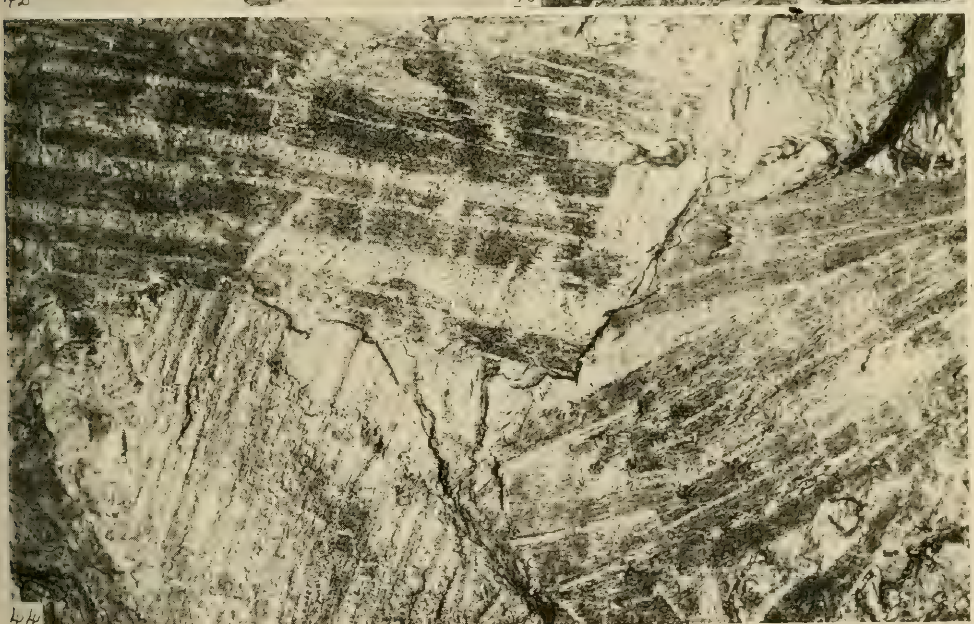


Figs. 21–26



FIGS. 27–41





Figs. 42–44

FIG. 11.—Part of the thin cross-section shown in Figure 5, at a higher magnification. *a*-1 is a thin anthraxylon chip, showing some plant structure; *d*-2, a thin sheet of attritus, containing a large amount of spore matter, some humic matter, and some earthy matter; *a*-3, anthraxylon chips; *d*-4, attritus. × 200.

FIG. 12.—Part of a thin horizontal section of coal from Terre Haute, Indiana. While the cross-sections reveal but very little plant or woody structure, every horizontal section shows a large amount of it, as in this section. × 150.

PLATE VII

FIG. 13.—A close-up view in a typical Wisconsin peat bog.

FIG. 14.—A lump of dried peat from the bog shown in Figure 13, showing thin chips of woody peat or anthraxylon, imbedded in the attritus. Compare this with Figure 4. Natural size.

FIG. 15.—The thin flat pieces of woody peat, picked out of the lump shown in Figure 14. Natural size.

PLATE VIII

FIG. 16.—Part of a thin cross-section of the coal from Ziegler, Illinois, containing a large proportion of cuticular matter. × 10.

FIG. 17.—Part of a thin cross-section of coal similar in appearance and composition as that shown in Figure 16. The heavy white lines running across the photograph represent leaf cuticles imbedded in matter largely derived from leaves. × 200.

FIG. 18.—One of the cuticles separated from the coal and seen flat-wise. × 200.

FIG. 19.—Part of a thin cross-section of a Pittsburgh coal with a number of thin anthraxylon strips. *d*-1, attritus rich in humic matter; *a*-2, thin anthraxylon strips rich in resinous matter; *d*-3, attritus; *a*-4, anthraxylon strips; *d*-5, thin layer of attritus; *a*-6, anthraxylon strip; *d*-7, attritus. Cell structures have been retained in *a*-4 and *a*-6. × 200.

FIG. 20.—Part of a thin cross-section of Pittsburgh coal rich in attritus. *d*-1, attritus composed of humic matter, spore-exines and carbonaceous matter. *a*-2, a thin anthraxylon layer; *d*-3 attritus composed of humic matter, spore-exines, and carbonaceous matter; *a*-4, a very thin strip of anthraxylon; *d*-5 and *d*-7, attritus, composed chiefly of spore-exines, some humic and carbonaceous matters, including thin strips of anthraxylon.

PLATE IX

FIG. 21.—Part of a thin cross-section of the coal from the Pittsburgh seam, at a very high magnification, showing the constituents in detail: spore-exines, in white; humic matter in gray; resinous particles, homogeneous gray, and carbonaceous matter in black. × 1,000.

FIG. 22.—Part of a thin horizontal section through a layer of attritus largely composed of spore matter, some humic matter, and some carbonaceous matter. The small circular to oval spots represent spore-exines; the irregular black spots, carbonaceous matter. × 150.

FIG. 23.—Part of a thin cross-section of coal, showing resinous particles in the anthraxylon and in the attritus.

FIG. 24.—Part of the thin horizontal section of Pittsburgh coal shown in Figure 22, at a very high magnification, showing the spore-exines and other constituents in detail. The spores are characteristic of the Pittsburgh bed. × 1,000.

FIG. 25.—Part of a thin horizontal section of coal from the Pittsburgh seam, at a very high magnification, showing the pollen grain type of spore-exines, imbedded in a matrix consisting of humic, carbonized, mineral, and earthy matter. × 1,000.

FIG. 26.—Part of a thin cross-section of anthraxylous coal from the Vandalia mine, Terre Haute, Indiana, showing a large number of oval resinous particles. The original woody issues have decayed in the part shown. × 200.

PLATE X

Spore-exines isolated from various coals by means of Schulze's reagent and seen flat-wise.

FIG. 27.—Spore-exine found in the coal from Buxton, Iowa. × 1,000.

FIG. 28.—Spore-exine predominant in and characteristic of the coal from Buxton, Iowa. × 1,000.

FIG. 29.—Spore-exine predominant in and characteristic of the Pittsburgh seam.

FIG. 30.—Exine of a pollen grain, common in all coals. × 1,000.

FIG. 31.—Spore-exine characteristic of and predominant in the coal from Shelbyville, Illinois. × 1,000.

FIG. 32.—Spore-exine characteristic of and predominant in the coal from the Sipsey mine, Alabama, Black Creek bed. × 1,000.

FIG. 33.—Spore-exine from bed No. 6, Illinois coal. × 1,000.

FIG. 34.—Spore-exines from an Illinois coal, bed No. 6. × 1,000.

FIG. 35.—Megaspore-exines of a smaller type, found in large numbers in the Shelbyville coal and occasionally in other coals. A megaspore similar to this but with three large air sacks is characteristic of coal from Buxton, Illinois. × 33.

FIG. 36.—Seedlike spore-exine from the Illinois coals, bed No. 6. × 100.

FIG. 37.—Spore-exine found in the coal from bed No. 5, Vandalia, Indiana. × 1,000.

FIG. 38.—Megaspore-exine predominant in the coal from Shelbyville, Illinois, but found occasionally in other coals. × 33.

FIG. 39.—Spore-exines, Spencerite type, common in all coals. × 100.

FIG. 40.—Spore-exine very common in the coal from Sessor, Illinois, but found in other coals from bed No. 6. × 1,000.

FIG. 41.—A spore-exine common in all coals.

PLATE XI

FIG. 42.—Cross-section of a pyritized fossil stem of Medullosa Anglica, showing three steles, surrounded by a common periderm; next to this is the inner cortex forming the outermost zone of tissues. The inner and outer cortexes are pervaded by leaf traces and gum ducts, both recognizable, though not distinctly in the photograph.

FIG. 43.—Part of a cleavage surface of coal, showing a large number of "rodlets" or "needles" imbedded helter-skelter in the attritus. × 10.

FIG. 44.—Part of a horizontal cleavage plane of coal showing a Medullosa type of woody structure, in which "needles" or "rodlets" form part of the tissue. × 3.

A QUANTITATIVE MINERALOGICAL CLASSIFICATION OF IGNEOUS ROCKS—REVISED

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PART III

CLASS 2, ORDER 3

(237) **Calcigranite.** No plutonic rock falling near the center point of this family has yet been located.

Quartz-ciminite. Among the extrusives the only rock found in this family is a quartz-bearing ciminite described by Washington.[1] Ciminite, named from its occurrence on Monti Cimini, Italy, was defined[2] as consisting of alkali feldspar, basic plagioclase, augite, and olivine, with accessory magnetite and apatite. From two modal analyses given, it appears that there are quartz-bearing and quartz-free ciminites; consequently the two divisions, quartz-ciminite and ciminite, are here made. A modal analysis of one rock, here called quartz-ciminite, gives orthoclase (Or_6Ab_1) 43.6 per cent, labradorite (Ab_1An_2) 16.1 per cent, quartz 4.6 per cent, apatite 0.7 per cent, augite 22.4 per cent, olivine 11.7 per cent, and magnetite 0.9 per cent. Since this rock contains olivine, it is not representative of the normal extrusives of the family.

(238) **Calciadamellite.** This is a quartz-monzonite whose plagioclase is labradorite. Here fall four specimens from the Elkhorn district, Montana, on the border of the Butte batholith, described by Barrell.[3] The rock, however, is near the border line between Orders 2 and 3. The plagioclase is described as

[1] Henry S. Washington, "Italian Petrological Sketches, II: The Viterbo Region," *Jour. Geol.*, IV (1896), 838.

[2] *Ibid.*, V (1897), 351; "The Roman Comagmatic Region," *Carnegie Publication No. 57* (Washington, 1906), p. 65.

[3] Joseph Barrell, "Microscopical Petrography of the Elkhorn Mining District, Jefferson County, Montana," *U.S. Geol. Surv., Ann. Rept.*, XXII, Part II (1901), p. 538.

"Ab_1An_1 or more basic" by Barrell. On the other hand, Cross, Iddings, Pirsson, and Washington[1] assume, by calculation from the chemical analysis of a specimen from the Butte region, that the plagioclase has Ab_1An_1 centers but more acid borders. The orthoclase in their analysis, however, was calculated as pure potash feldspar, while as a matter of fact it contains considerable soda. Consequently the plagioclase may be, as Barrell says, more basic, and the C.I.P.W. rock would fall in the calciadamellite family with Barrell's rock.

(239) Granogabbro JOHANNSEN.[2] See note under granodiorite (229) and leuco-granogabbro (139).

Rhyobasalt. To have a term analogous to granogabbro, the term rhyobasalt is here used. See note under granodiorite (229).

(2310) Quartz-gabbro.
Quartz-olivine-gabbro.
Quartz-basalt.
Quartz-olivine-basalt.

(2312) **Calcisyenite.** No modal analysis of a plutonic rock belonging here has yet been located.

Vulsinite WASHINGTON. Vulsinites are defined by Washington[3] as "effusive rocks occupying an intermediate position between the trachytes and the andesites. They are characterized mineralogically by the presence of alkali feldspar with a large amount of basic plagioclase (labradorite to anorthite) together with augite and diopside. Hornblende and biotite are not abundant in the type specimens, though they may be present in large amounts in other varieties. . . . . Olivine is wanting, or if present is so in only accessory amounts." While the definition would suggest a rock of the latite series, the modal analysis of the Bolsena type[4] shows it to belong to Family 12. The mineral percentages

[1] Cross, Iddings, Pirsson, and Washington, *Quantitative Classification of Igneous Rocks* (Chicago, 1903), p. 227.

[2] Albert Johannsen, "Suggestions for a Quantitative Mineralogical Classification of Igneous Rocks," *Jour. Geol.*, XXV (1917), 89.

[3] Henry S. Washington, "Italian Petrological Sketches, I: The Bolsena Region," *Jour. Geol.*, IV (1896), 553.

[4] *Ibid.*, "The Roman Comagmatic Region," *Carnegie Publication No. 57* (Washington, 1906), p. 65.

are: soda-orthoclase (Or_9Ab_4) 69.5, basic plagioclase (anorthite phenocrysts 6.1, labradorite groundmass 11.9, average Ab_1An_2) 18.0, augite 7.4, biotite 1.0, ores 3.6, apatite 0.4, titanite 0.1.

Ciminite WASHINGTON. The quartz-free ciminite has a mode[1] of soda-orthoclase ($Or_{10}Ab_3$) 50.7 per cent, labradorite (Ab_1An_2) 13.1 per cent, augite 23.2 per cent, olivine 11.2 per cent, magnetite 0.9 per cent, apatite 0.9 per cent. See note under quartz-ciminite (237).

(2313) **Calcimonzonite.** The original Monzoni monzonite, according to Brögger, usually contains a basic plagioclase (see note under 2213). In the present classification normal orthoclase-acid-plagioclase rocks are included under the term monzonite and orthoclase-basic-plagioclase (excluding anorthite) rocks under the term calcimonzonite.

Calcilatite. The extrusive equivalent of the preceding.

(2314) **Monzogabbro (monzonorite).** The rocks which fall in this family are described in the literature as gabbros, norites, or monzonites. The term syenogabbro, originally proposed[2] for this family, is here withdrawn, and the term monzogabbro substituted for reasons stated under granodiorite (229). Another reason why syenogabbro should not be used for the plutonic rock of this family is that, by analogy, the extrusive should then be called trachy-basalt. But Bořický[3] used the term trachy-basalt for rocks which are now called monchiquites.

Basalatite. Basalatite, as intermediate between basalt and latite, is here suggested. It corresponds in form with its deep-seated equivalent, monzogabbro.

(2315) Gabbro VON BUCH. The term gabbro (*granito di gabbro*) was used by Targioni Tozzetti[4] and other writers for diallage-serpentine and related rocks from Tuscany. Von Buch[5] applied

[1] Henry S. Washington, "The Roman Comagmatic Region," *Carnegie Publication No. 57* (Washington, 1906), p. 32.

[2] Albert Johannsen, *op. cit.*, p. 89.

[3] Emanuel Bořický, "Petrographische Studien an den Basaltgesteinen Böhmens," *Arch. f. d. naturw. Landesdurchf. v. Böhmen*, II (1874), Abt. ii, Th. ii, p. 44.

[4] Targioni Tozzetti, *Relazioni d'alcuni viaggi fatti in diverse parti della Toscana* (Firenze, 1768), II, 432.

[5] Leopold von Buch, "Ueber den Gabbro" (read in Akad. d. Wissens., Berlin, October 12, 1809), *Magazin d. Gesell. naturf. Freunde z. Berlin*, IV (1810), 128–49.

it to rocks consisting of "Saussurit oder Jade und Smaragdit, oder häufiger aus Feldspath und Smaragdit . . . . oder auch seltener aus allen diesen Substanzen vereinigt." His saussurite is altered feldspar, the jade amphibole, and the smaragdite probably green diallage. For a long time the name continued to be applied to plagioclase-diallage rocks, but in recent years the kind of pyroxene has been disregarded, and only the basic character of the plagioclase has been considered essential to the definition. In the present classification, therefore, gabbro is simply a rock consisting essentially of labradorite or bytownite and a biopyribole. Olivine may be an accessory, and magnetite is usually present in variable amounts. The orthoclase-gabbro of Streng[1] and Irving[2] is really diallage-monzonite or monzodiorite.

Hornblende-gabbro.
Olivine-gabbro.
Quartz-gabbro.
Uralite-gabbro, etc.

Norite ESMARK. Esmark[3] applied the name norite to certain Norwegian rocks which belong in part to the rocks now called norites, but in part to the diorites. Scheerer[4] applied it to rocks related to the gabbros and hyperites. Rosenbusch[5] limited it to rocks containing essential hypersthene and plagioclase, and said that unless so limited the term would be meaningless, and later[6] gave the constituents as basic plagioclase and an orthorhombic pyroxene. In this sense it is now generally used.

Hyperite TÖRNEBOHM. These rocks, intermediate between gabbros and norites, and containing both orthorhombic and monoclinic pyroxenes, were originally called hypersthenites

[1] Aug. Streng, "Über die kristallinischen Gesteine von Minnesota in Nordamerika," *Neues Jahrb.* (1877), pp. 113–38.

[2] Roland Duer Irving, "The Copper-bearing Rocks of Lake Superior," *U.S. Geol. Surv., Mono. 5* (1883), pp. 50–52.

[3] Esmark, *Magazin für Naturvidenskaberne*, I, 207.

[4] Th. Scheerer, *Gaea Norvegica*, Heft ii, 313; also "Geognostisch-mineralogische Skizzen gesammelt auf einer Reise an der Süd-Küste Norwegens," *Neues Jahrb.* (1843), p. 668.

[5] H. Rosenbusch, *Mikroskopische Physiographie der massigen Gesteine* (1st ed.; Stuttgart, 1877), p. 477.

[6] *Ibid.* (4th ed., 1907), p. 348.

by Rose.[1] The name was too suggestive of a rock entirely composed of hypersthene; therefore Törnebohm[2] gave to them the name hyperite, although this term had previously been used by Senft[3] for his group composed of eclogites, gabbros, and hypersthenites.

Syn.: Hypersthene-syenit, Hypersthenite Rose, Hypersthene-gabbro, Augite-norite, etc.

Basalt. The derivation of the term is unknown. It may be derived from the Ethiopian *bsalt*, "cooked," suggesting a baked rock, or from *barzalten*, *barzel*, the Hebrew for "iron." Pliny[4] speaks of "basalten" found in Ethiopia, a rock which "in color and hardness resembles iron, and is used in making statuary." Agricola[5] thought that certain rocks in Saxony were identical with the basalt of the older writers, and applied this term to them, and Werner[6] used it for the same rocks, which he considered sedimentary. Basalt is the extrusive equivalent of gabbro, and in general the term is applied to rocks with basic plagioclase and augite, with or without olivine. Some writers apply the term to plagioclase-augite rocks with olivine, irrespective of the kind of plagioclase, though in general, at the present time, this is not the basis of separation from the andesites. On the basis of the feldspar, therefore, there would be

With acid plagioclase	Hornblende-andesite Augite-andesite Olivine-augite-andesite, etc.
With basic plagioclase	Hornblende-basalt Basalt (with pyroxene) = Auganite Winchell Olivine-basalt, etc.

[1] G. Rose, "Über Hypersthenit," *Pogg. Ann.*, XXXIV (1835), 10.

[2] A. E. Törnebohm, "Über die wichtigeren Diabas- u. Gabbro-Gesteine Schwedens," *Neues Jahrb.* (1877), p. 379.

[3] Ferdinand Senft, *Classification und Beschreibung der Felsarten* (Breslau, 1857), p. 59.

[4] C. Plinii Secundi *Naturalis Historiae* xxxvi. cap. vii. Ed. Lugd. Batav. Roterodami, Ao. 1668, p. 645.

[5] Georg Agricola (Georg Bauer), *De re metallica*, 1556.

[6] A. G. Werner, "Bekanntmachung einer . . . . über die Entstehung des Basaltes gemachten Entdeckung . . . . ," *Bergmänn. Journ.*, Pt. II (1788), p. 845.

Winchell[1] suggests the word auganite for olivine-free basalt, and uses basalt for the olivine-bearing variety. The writer prefers basalt and olivine-basalt for these rocks.

According to their textures, basalts have been divided into three groups: basalts proper, anamesite, and dolerite.

Basalt proper. Compact, dense, aphanitic.

Anamesite VON LEONHARD.[2] Megascopically crystalline, but fine-grained. Name derived from *ἀνάμεσος*, "in the middle."

Dolerite HAÜY,[3] from *δολερὸς*, "deceptive." Coarse-grained.

Alboranite BECKE. Becke[4] proposed the term alboranite for certain extrusive rocks from the island of Alboran. They consist of hypersthene and basic plagioclase. The phenocrysts in the rocks described by him are anorthite and the groundmass microlites labradorite. The rocks thus are olivine-free hypersthene-basalts, and, as extrusive representatives of norite, deserve the new name. See note under santorinite (2215).

(2323) Kulaite WASHINGTON. This term was originally applied by Washington[5] to certain extrusive rocks from the volcanoes of Kula, in Lydia, Asia Minor, under the impression that they were hornblende-basalts. Later they were shown by him[6] to be nephelite-bearing and to contain approximately equal amounts of orthoclase and basic plagioclase. No plutonite of this composition has yet been located among modes given in the literature; therefore kulaite is temporarily used as the family name. The term should not be confused with kullait HENNIG.

[1] Alexander N. Winchell, "Rock Classification on Three Co-ordinates," *Jour. Geol.*, XXI (1913), 215; also "Geology of the National Mining District, Nevada," *Mining and Scientific Press*, CV (1912), 657.

[2] Karl Cäsar von Leonhard, *Die Basalt-Gebilde in ihren Beziehungen zu normalen und abnormen Felsmassen* (Stuttgart, 1832), I, 151.

[3] Ascribed to Haüy by Alexandre Brongniart, *Classification et caractères minéralogiques des roches* (Paris, 1827), p. 101.

[4] F. Becke, "Der Hypersthen-Andesit der Insel Alboran," *Tscherm. Min Petr. Mitth.*, XVIII (1899), 553.

[5] Henry S. Washington, "On the Basalts of Kula," *Amer. Jour. Sci.*, XLVII (1894), 115.

[6] *Ibid.*, "The Composition of Kulaite," *Jour. Geol.*, VIII (1900), 618.

Loewinson-Lessing[1] expressed the opinion that kulaite is the extrusive equivalent of heumite, with which the present writer does not agree. Heumite is described by Brögger[2] as a rock essentially of soda-orthoclase or soda-microcline with other feldspars, very small amounts of nephelite and sodalite, and considerable barkevikite and biotite. Furthermore, the leucocratic minerals in heumite form only 53 per cent of the rock, and the subordinate plagioclase is oligoclase-albite, and not basic plagioclase.

(2324) **Nephelite-(leucite-)monzogabbro.** A term suggested here for the nephelite-(leucite-)bearing rocks of the basic plagioclase series, and comparable to the granogabbros among those bearing quartz. Nephelite-syenogabbro, suggested previously,[3] is withdrawn. See notes under (229) and (2314).

Essexite SEARS is quite variable, but probably belongs here or to (2325), or to both, although the original description by Sears[4] does not mention the presence of orthoclase. He says it contains augite, hornblende, biotite, plagioclase, and nephelite with the usual accessories. Washington,[5] describing the same rock, says that it is essentially a basic monzonitic rock in which feldspathoids and both lime-soda and alkali feldspars are present. The feldspar ranges from Ab_1An_1 to Ab_1An_2, and "an alkali-feldspar is not uncommon . . . . often microperthitic." Nephelite is fairly abundant. In another specimen the plagioclase was Ab_1An_3 and only a few grains of alkali-feldspar were seen. Speaking of certain other rocks described as essexites, Washington[6] says that since they contain neither nephelite nor alkali-feldspar, they are not essexites. Many rocks, clearly not essexites, have been described

[1] F. Loewinson-Lessing, "Kritische Beiträge zur Systematik der Eruptivgesteine, V," *Tscherm. Min. Petr. Mitth.*, XXI (1902), 322.

[2] W. C. Brögger, *Die Eruptivgesteine des Kristianiagebietes. III: Das Ganggefolge des Laurdalits* (Kristiania, 1898), pp. 98–113.

[3] Albert Johannsen, "Suggestions for a Quantitative Mineralogical Classification of Igneous Rocks," *Jour. Geol.*, XXV (1917), 89.

[4] John H. Sears, "Elaeolite-Zircon-Syenites and Associated Granitic Rocks in the Vicinity of Salem, Essex County, Massachusetts," *Bull. Essex Inst.*, XXIII (1891), 146.

[5] Henry S. Washington, "The Petrographical Province of Essex County, Massachusetts," *Jour. Geol.*, VII (1899), 53–56.

[6] *Loc. cit.*

under this name. The original rock is apparently of Class 2 (though some recently described essexites are of Class 3), and certainly of Order 3.

(2325) Nephelite-(leucite-)gabbro. Rouvillite O'NEILL belongs here. This is a rock from St. Hillaire, Quebec, described by O'Neill.[1] It may be called a nephelite-gabbro or light-colored theralite. Rosiwal measurements show the rock to consist of nephelite 29.35 per cent, plagioclase ($Ab_{50}An_{50}$ to $Ab_{20}An_{80}$) 55.9 per cent, apatite 1.15 per cent, pyroxene 7.50 per cent, and hornblende 3.64 per cent.

(2327) Heronite COLEMAN. While this is an analcite dike rock, and far from the center point of the family, it is the only rock so far located in this pigeonhole. The name was given by Coleman[2] to a rock from Heron Lake, north of Lake Superior, consisting of much analcite (53 per cent of the leucocratic minerals), orthoclase (28.24 per cent), labradorite (13 per cent), aegirite (4.04 per cent), and limonite and calcite.

(2330) Lugarite TYRRELL[3] is a porphyritic rock, occurring in dikes and as a sill in the Lugar teschenite-picrite complex in the west of Scotland. It consists of analcite (with some nephelite) 50 per cent, labradorite 10 per cent, apatite 2 per cent, titanaugite 20 per cent, barkevikite 15 per cent, and ilmenite 3 per cent. Tyrrell considers the analcite "original, displacing nephelite."

CLASS 2, ORDER 4

(247) **Anorthite**-granite.

(248) **Anorthite**-adamellite.

(249) **Anorthite-granogabbro.**

(2410) Quartz-anorthite-gabbro.

(2412) **Anorthite**-syenite. A syenite whose small percentage of plagioclase is anorthite may be called anorthite-syenite. Here belongs a so-called shonkinite from Elkhorn, Montana, described

[1] J. J. O'Neill, "St. Hilaire (Beloeil) and Rougemont Mountains, Quebec," *Geol. Surv. Canada, Mem. 53* (Ottawa, 1914), p. 35.

[2] A. P. Coleman, "A New Analcite Rock from Lake Superior," *Jour. Geol.*, VII (1899), 435.

[3] G. W. Tyrrell, "The Late Palaeozoic Alkaline Igneous Rocks of the West of Scotland," *Geol. Mag.*, IX (1912), 77–78.

by Barrell.[1] It is hardly typical of the family, however, since it is near the boundary of Class 3. See note under (2112).

(2413) **Anorthite-monzonite.** See note under (2113).

(2414) **Anorthite-monzogabbro.** See notes under (2114) and (2314).

(2415) Anorthite-gabbro. Here belongs an anorthite-augite dike rock from the Carlingford district, Ireland, with the percentages 62 and 38 according to a calculated analysis by Roth.[2] The corresponding extrusive rock, with more than 50 per cent anorthite, 33 per cent augite, and 8 per cent magnetite, was described as anorthite-diabase by Tschermak.[3]

Another rock belonging to this family is kyschtymite MOROZEWICZ,[4] an anorthite-corundum rock, occurring as an intrusive in granite in Kyschtym in the Urals. Still another is allivalite HARKER,[5] occurring on Allival, a mountain on the Isle of Rum and consisting of anorthite and olivine.[6] Finally, there is rougemontite O'NEILL,[7] containing anorthite 52.25 per cent, augite 32.51 per cent, olivine 8.35 per cent, hornblende 0.43 per cent, and iron ore 6.52 per cent.

CLASS 3, ORDER I

(316) **Mela-orthogranite.** In this family fall two rocks, Prowersose (of the quantitative system of C.I.P.W.), described by Cross,[8] a dike rock from Two Buttes, Colorado, and a similar rock

[1] Joseph Barrell, "Microscopical Petrography of the Elkhorn Mining District, Jefferson County, Montana," *U.S. Geol. Surv., Ann. Rept.*, XXII, Part II (1901), p. 519.

[2] J. Roth, *Gesteinsanalysen*, lvii. The rock was originally calculated by G. Haughton (*Quart. Jour. Geol. Soc.*, XII [1856], 197) as anorthite 85.84 per cent and augite 14.16 per cent, which was shown to be wrong by Roth.

[3] Gustav Tschermak, "Über secundäre Mineralbildungen in den Grünsteingebirge bei Neutitschein," *Sitzungsber. d. Wien Akad. d. Wiss.*, XL (1860), 127.

[4] J. Morozewicz, "Kyschtymit—ein Korund-Anorthitgestein," *Tscherm. Min. Petr. Mith.*, XVIII (1898), 202.

[5] Alfred Harker, "Igneous Rocks from the Ultrabasic Group of the Isle of Rum. Summary of Progress," *Geol. Surv.* (1903), p. 56.

[6] J. W. Judd, "On the Tertiary and Older Peridotites of Scotland," *Quart. Jour. Geol. Soc.*, XLI (1883), 389–90, 395.

[7] J. J. O'Neill, "St. Hilaire (Beloeil) and Rougemont Mountains, Quebec," *Geol. Surv. Canada, Mem. 43* (Ottawa, 1914), p. 77.

[8] Whitman Cross, "Prowersose (Syenitic Lamprophyre) from Two Buttes, Colorado," *Jour. Geol.*, XIV (1906), 165.

from Knox County, Maine, described by Bastin.[1] They are melanocratic orthogranites.

(317) **Mela**-albite-granite. A poor name, which should be replaced owing to the former use of albite-granite for a different kind of rock. See note under (217).

(318) **Mela-albite**-adamellite. See note under (218).

(319) **Mela-albite**-granodiorite. See note under (219).

(3110) **Mela-albite**-tonalite. See note under (2110).

(3111) **Mela-orthosyenite.** See note under (2111).

(3112) **Mela-albite**-syenite. See note under (2112).

(3113) **Mela-albite**-monzonite. See note under (2113).

(3114) **Mela-albite-monzodiorite.** See note under (2114).

(3115) **Mela-albite**-diorite. See note under (2115).

(3116) **Orthoshonkinite.** Weed and Pirsson[2] gave the name shonkinite (from Shonkin, the Indian name for the Highwood Mountains, Montana) to a melanocratic "granular plutonic rock consisting of essential augite and orthoclase. . . . . It may be with or without olivine, and accessory nepheline, sodalite, etcetra, may be present in small quantities." In another place[3] they state that "a triclinic striated feldspar is also present, but in no considerable amount. . . . . It is albite." The amount of albite is not mentioned, but it is included in the estimated amount of alkali-feldspar. Based on the definition, however, no albite is necessary, and by analogy with other rocks (see under (111)) the term orthoshonkinite may be applied to the rocks as defined with less than 5 per cent albite. Where the albite percentage is greater, the rock falls into Family 17 as albite-shonkinite or shonkinite simply. While the original rock contained traces of feldspathoids, by definition none is necessary, and none is shown in the mode of this rock as given by Washington.[4] It has, however, affinities with the nephelite rocks; consequently, though it may fall on the feldspar base line of the double triangle, it is to be classed with the

[1] Edson S. Bastin, "Some Unusual Rocks from Maine," *Jour. Geol.*, XIV (1906), 173–80.

[2] Walter H. Weed and Louis V. Pirsson, "Highwood Mountains of Montana," *Bull. Geol. Soc. Amer.*; VI (1895), 415–16.

[3] *Ibid.*, p. 412.

[4] Henry S. Washington, "The Foyaite-Ijolite Series of Magnet Cove: A Chemical Study in Differentiation," *Jour. Geol.*, IX (1901), 613.

feldspathoid rocks in Family 16. Furthermore, a modal analysis of another rock[1] shows alkali-feldspar 20 per cent, nephelite 5 per cent, sodalite 1 per cent, apatite 4 per cent, and mafites 70 per cent (10 of which is olivine). The latter rock, consequently, may be called a nephelite-shonkinite of Family 21.

(3117) Shonkinite. This is albite-bearing shonkinite. See note under (3116).

(3121) **Nephelite**-shonkinite. See note under (3116).

(3124) **Melalitchfieldite.** See note under (2124).

(3125) **Melamariupolite.** See note under (2125).

(3131) Bekinkinite ROSENBUSCH and Missourite WEED and PIRSSON.

The melanocratic nephelite plutonic rock of this family is represented by bekinkinite, named by Rosenbusch[2] from its occurrence on Mount Bekinkina on the peninsula Ambavatoby, as described by Lacroix.[3] While the original rock is said to contain a small amount of anorthoclase, the definition of the type rock of Rosenbusch does not require it. He calls it a plutonic form of nephelite basalt, and says it is related to ijolite as missourite is to fergusite.

Missourite was named by Weed and Pirsson[4] from its occurrence on the Missouri River. It is a melanocratic, feldspar-free leucite rock. It contains 16 per cent leucite, 8 per cent analcite and zeolites, 50 per cent augite, 6 per cent biotite, and 5 per cent iron ore.

Farrisite BRÖGGER[5] is a melanocratic melilite rock of this family.

Mela-nephelite-basalt is the extrusive equivalent of bekinite, **mela**-leucite-basalt of missourite, and **mela**-melilite-

[1] Louis V. Pirsson, "Petrography and Geology of the Igneous Rocks of the Highwood Mountains, Montana," *U.S. Geol. Surv., Bull. 237* (1905), p. 104.

[2] H. Rosenbusch, *Mikroskopische Physiographie der massigen Gesteine* (4th ed.; Stuttgart, 1907), p. 441.

[3] A. Lacroix, "Sur quelques roches ijolithiques du Kilima-Ndjaro," *Bull. Soc. Min. France*, XXIX (1906), 90.

[4] Walter H. Weed and Louis V. Pirsson, "Missourite, a New Leucite Rock from the Highwood Mountains of Montana," *Amer. Jour. Sci.*, II (1896), 323; Louis V. Pirsson, "Petrography and Geology of the Igneous Rocks of the Highwood Mountains, Montana," *U.S. Geol. Surv., Bull. 237* (1905), p. 118.

[5] W. C. Brögger, *Die Eruptivgesteine des Kristianiagebietes. III: Das Ganggefolgschaft des Laurdalits* (Kristiania, 1898), p. 70.

basalt or **mela**-melilitite of farrisite. There are also analcite-basalts, most of which belong in this family, though some fall in Class 2.

CLASS 3, ORDER 2

(327) **Melagranite.** See note under (127).

(328) **Mela-adamellite.** See notes under (127) and (228).

(329) **Melagranodiorite.** See notes under (127) and (229).

(3210) **Melatonalite.** See notes under (127) and (2210).

(3212) **Melasyenite.** See notes under (127). Some years ago Weed and Pirsson[1] described a rock from the Highwood Mountains as containing about equal amounts of light and dark constituents, and gave to it the name yogoite. Their series of rocks as given was:

All orthoclase, no augite	=	sanidinite.
Orthoclase exceeds augite	=	augite-syenite.
Orthoclase equals augite	=	yogoite.
Augite exceeds orthoclase	=	shonkinite.
All augite, no orthoclase	=	pyroxene and peridotite rocks of various types.

Later[2] they withdrew the name yogoite since they found that it fell into Brögger's monzonite group on account of the proportions of orthoclase and plagioclase. The original yogoite, computed in the present system, falls in (2212) and is a normal monzonite, but associated with it, on Yogo Peak, and called shonkinite[3] by Weed and Pirsson, are two other rocks which differ from normal shonkinites in being associated with quartz-bearing instead of with feldspathoid-bearing rocks and in containing andesine instead of albite. They also contain more soda-orthoclase than andesine. These "shonkinites," therefore, may well take upon themselves the discarded name yogoite, since they also occur on Yogo Peak, and fit into the foregoing scheme even better than the original yogoite.

(3213) **Melamonzonite.** See note under (127) and (2213). Here belongs a basic contact monzonite of the Coryell batholith,

[1] W. H. Weed and L. V. Pirsson, "Igneous Rocks of Yogo Peak, Montana," *Amer. Jour. Sci.*, L (1895), 479.

[2] W. H. Weed and L. V. Pirsson, "The Bearpaw Mountains of Montana," *Amer. Jour. Sci.*, I (1896) 357–58.

[3] L. V. Pirsson, "Petrography of the Igneous Rocks of the Little Belt Mountains, Montana," *U.S. Geol. Surv., Ann. Rept.*, XX, Part III (1900), p. 487.

described by Daly,[1] as well as a contact rock against granite described by Miller.[2]

(3214) **Melamonzodiorite.** Based on Daly's[3] average analysis of 161 basalts, as named by the original authors, Leith and Mead[4] computed the mineral composition of the average "basalt" and found that it contained oligoclase 35.4, orthoclase 10.75, augite 36.90, olivine 7.58, magnetite 5.80, ilmenite 0.73, and titanite 2.84. This rock, according to the computed mode, therefore, is not of the gabbro family at all, but of the monzodiorite. Included in Daly's average, of course, are all rocks named "basalts" by the original authors, consequently including many which at the present time would be called andesites.

(3215) **Mela**diorite. Here belong, among dike rocks, many camptonites, kersantites, and spessartites, and some diabases and basalts, though most of the latter rocks belong to Class 2. Among deep-seated rocks there are a few meladiorites.

(3217) **Oligoclase-**shonkinite. **Andesine-**shonkinite. It would be very desirable if there were terms to express the acid-plagioclases exclusive of albite (Ca*N*af, of the present system) and the basic plagioclases exclusive of anorthite (Na*Ca*f). Rosenbusch[5] found the same difficulty when in his description of granite he said: "Oligoklas steht hier und im Folgenden für sauren Plagioklas." A single term would thus cover the rocks of this family. See note under (3116).

CLASS 3, ORDER 3

(337) **Mela-calcigranite.** This term is too awkward. The only modal analysis yet found in this family does not lie near the center point.

(339) **Melagranogabbro.** See notes under (127) and (239).

[1] Reginald A. Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Geol. Surv. Canada, Mem. 38*, Part I (1912), p. 361.

[2] William J. Miller, "Geology of the North Creek Quadrangle, Warren County, New York," *N.Y. State Museum, Bull. 170* (1914), p. 37.

[3] Reginald A. Daly, "Average Chemical Compositions of Igneous Rock-Types," *Proc. Amer. Acad. Arts and Sci.*, XLV (1910), 224.

[4] C. K. Leith and W. J. Mead, *Metamorphic Geology* (New York, 1915), p. 74.

[5] H. Rosenbusch, *Elemente der Gesteinslehre* (Stuttgart, 1898), p. 76.

(3310) **Mela**-quartz-gabbro. Too awkward a term. There are three rocks in this family, but all of them are melanocratic hornblende-quartz-gabbros—an "abnormal hornblende-gabbro" in the Moyie sill described by Daly,[1] a quartz-bearing gabbro from the Purcell sill, also described by Daly,[2] and a hornblende-gabbro from Sepänlampi, Hauksuo, Kisko, described by Eskola.[3] The type of the family should be chosen from an augite rock.

(3314) **Melamonzogabbro.** See note under (2314). Here are included two essexites, a hornblende-gabbro, a hornblende-norite, and a so-called gabbro.

(3315) **Melagabbro.** See note under (2315). Many gabbros fall here, also a few norites, and some diabases and basalts (and "dolerites").

Melabasalt. The extrusive equivalent of the above. Arapahite WASHINGTON and LARSEN[4] belongs here.

(3317) **Labradorite-(bytownite-)**shonkinite. See note under (3217).

(3324) **Mela-nephelite-monzogabbro.** See note under (2324).

(3325) Theralite ROSENBUSCH. Theralite, from the Greek θηρᾶν ("eagerly looked for"), was applied by Rosenbusch[5] to plagioclase-nephelite rocks first thought to be represented by certain tephrites and basanites described by Wolff.[6] True theralites, however, were first described by Wolff[7] some years later. Besides the presence of plagioclase and nephelite, these rocks are characterized by much predominating dark constituent; consequently they belong to Class 3. Among the lime-soda feldspars of the rocks

[1] Reginald A. Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Geol. Surv. Canada, Mem. 38*, Part I (1912), p. 234.

[2] *Ibid.*, p. 224.

[3] Pentti Eskola, "On the Petrology of the Orijärvi Region in Southwestern Finland," *Bull. d. l. com. géol. d. Finlande* (Helsingsfors), 1914, p. 71.

[4] Henry S. Washington and E. S. Larsen, "Magnetite Basalt from North Park, Colorado," *Jour. Wash. Acad. Sci.*, III (1913), 452.

[5] H. Rosenbusch, *Mikroskopische Physiographie der massigen Gesteine* (2d ed.; Stuttgart, 1887), p. 248.

[6] J. E. Wolff, "Notes on the Petrography of the Crazy Mts., and Other Localities in Montana Territory," *Northern Transcontinental Survey* (1885), pp. 8–13.

[7] J. E. Wolff, "On the Occurrence of Theralite in Costa Rica, Central America", *Amer. Jour. Sci.*, I (1896), 271.

classed by Rosenbusch[1] as theralites "ist die Labradoritmischung die herrschende, nach auszen hin aufsteigend bis zum Andesin, in den Kernen sinkend bis an die Grenze zum Bytownit." The average feldspar, therefore, is basic plagioclase. Olivine may or may not be present. In the rock from Costa Rica described by Wolff and called the true theralite type by Rosenbusch, who named it, the plagioclase is labradorite. The rock contains, however, a little orthoclase, not necessary in the type.

Kylite TYRRELL,[2] with 31 per cent labradorite, 4 per cent nephelite, 1.3 per cent analcite, 26 per cent titanaugite, 32 per cent olivine, and small amounts of ilmenite, biotite, and apatite, belongs here also. It is a plutonic rock occurring in the Kyle district of Ayrshire, whence its name.

Syn.: Olivine-theralite.

(3330) No plutonic rock has been located in this family, but a rock described as a pikrit-basalt by Quensel[3] from Juan Fernandez occurs among the extrusives. It contains 50 per cent or more of olivine.

CLASS 3, ORDER 4

(3414) **Ricolettaite.** The only rock located here is a dark calcic gabbro from Traversellitthal, north cliff of Ricoletta, Monzoni. It consists of orthoclase 5 to 7 per cent, anorthite 35 to 40 per cent, pyroxene 40 per cent, and a little biotite, olivine, and magnetite. It was described by Doelter[4] and deserves a new name.

(3415) Yamaskite YOUNG. This anorthite-augite rock from Mount Yamaska, Quebec, was described by Young.[5] A similar rock, but carrying olivine, was described by O'Neill.[6]

Olivine-yamaskite.

[1] H. Rosenbusch, *op. cit.* (4th ed., 1907), p. 413.

[2] G. W. Tyrrell, "The Late Palaeozoic Alkaline Igneous Rocks of the West of Scotland," *Geol. Mag.*, IX (1912), 121.

[3] P. D. Quensel, "Der Geologie der Juan Fernandezinseln," *Bull. Geol. Inst. Upsala*, XI (1912), 265.

[4] C. Doelter, "Chemische Zuzammensetzung und Genesis der Monzonitgesteine," *Tscherm. Min. Petr. Mitth.*, XXI (1902), 102.

[5] G. A. Young, "Geology and Petrography of Mount Yamaska, Quebec," *Geol. Surv. Canada, Ann. Rept.*, XVI, Part H (1906), p. 16.

[6] J. J. O'Neill, "St. Hilaire (Beloeil) and Rougemont Mountains, Quebec," *Geol. Surv. Canada, Mem. 43* (Ottawa, 1914), p. 66.

(3430) Several leucitites, so called, fall here, although they are not true leucitites on account of their feldspar content. No plutonic rocks have been located.

CLASS 4, ORDERS 1 TO 3

No attempt is made in this paper to separate the orders of Class 4, since too few modes have been found in the literature to warrant the separation, and measurements by the author, so far, have been chiefly on the rocks of the first three classes. It is hoped shortly to give the modes of some of the classic types of Class 4.

Family 1.—Dunite VON HOCHSTETTER. This rock, named by von Hochstetter[1] from the Dun Mountains, New Zealand, consists of olivine with accessory chromite. The amount of chromite varies greatly. Vogt[2] says that the normal rocks carry from 2 to 5 per cent. They would thus belong to Order 1. Dunites with between 5 and 95 per cent chromite he calls chromite-dunites. With over 95 per cent chromite the rocks may be classed as chromite ores of Order 4. They are represented by the plagioclase-free varieties of Sjögren's[3] Kromit-Olivinit. In other cases the ore is magnetite, as in the magnetite-olivinite series of Sjögren, which includes plagioclase-bearing and plagioclase-free olivine-magnetite rocks. Perhaps good subdivisions would be:

Order 1. Dunite. Olivine between 100 and 95 per cent.

Order 2. Chromite-dunite and magnetite-dunite. Olivine between 95 and 50 per cent.

Order 3. **Olivine-chromitite** and **olivine-magnetitite.** Olivine between 50 and 5 per cent.

Order 4. **Chromitite** and **magnetitite.** Olivine less than 5 per cent.

Families 2 and 5.—These are the families of the mica-(amphibole-)olivine rocks. Among them are mica-peridotite and

[1] Ferdinand von Hochstetter, "Dunit, körniger Olivinfels vom Dun Mountain bei Nelson, New-Seeland," *Zeitschr. d. d. geol. Gesell.*, XVI (1864), 341.

[2] J. H. L. Vogt, "Beiträge zur genetischen Classification der durch magmatische Differentiationsprocesse und der durch Pneumatolyse entstandenen Erzvorkommen," *Zeitschr. f. prak. Geol.* (1894), p. 391.

[3] A. Sjögren, "Om förekomsten af Tabergs jernmalmsfyndighet i Småland," *Geol. Fören. i Stockh. Förhandl.*, III (1876), 58.

amphibole-peridotite. Mica-peridotite was named by Diller[1] from an occurrence in Kentucky. In the type rock the olivine and its alteration products form over 80 per cent, the ores, magnetite, and ilmenite together 4.2 per cent, while biotite, garnet, etc., are accessory. The rock number is (412).

Amphibole-peridotite was first described as amphibole-gabbro by Howitt.[2] Later Rosenbusch[3] compared the same rock with the Schreisheim dike, and still later Verbeek[4] called it amphibole-peridotite. Hornblende-peridotite is the usual variety. Rocks of this class have been called hornblende-picrites by Bonney[5] and hudsonites by Cohen,[6] but since picrite was originally used for an olivine-augite rock and hudsonite for a variety of diallage, Williams[7] proposed for them the name cortlandtite.

A rock whose present mode places it in Family 5 is scyelite Judd.[8] It consists of hornblende 58.5 per cent, serpentine after olivine 22 per cent, mica 18.5 per cent, and magnetite 1 per cent. Judd says that the hornblende is probably secondary after augite; therefore it possibly should be placed in Family 11.

Families 3, 6, and 10.—In these pigeonholes fall valbellite Schäfer[9] and some of the olivinites of Sjögren[10] and

[1] J. S. Diller, "Mica-Peridotite from Kentucky," *Amer. Jour. Sci.*, XLIV (1892), 289; also "Peridotite of Elliott County, Kentucky," *U.S. Geol. Surv., Bull. 38* (1887), p. 11.

[2] A. W. Howitt, "The Diorites and Granites of Swift's Creek and Their Contact Zones, with Notes on the Auriferous Deposits," *Proc. Roy. Soc. Victoria*, 1879.

[3] H. Rosenbusch, review of preceding article, *Neues Jahrb.*, I (1881), 221.

[4] R. D. M. Verbeek, *Topographische en geologische beschrijving van een gedeelte van Sumatra's Westkust* (Batavia, 1883), p. 304; also "Description géologique de l'îel d'Ambon," *Jaarboek van het Mijnwegen in Nederl. Oost-Indie*, XXXIV (1905).

[5] T. G. Bonney, "On a Boulder of Hornblende-Picrite Near Pen-y-Carnisiog. Anglesey," *Quart. Jour. Geol. Soc.*, XXXVII (1881), 137.

[6] E. Cohen, "Berichtigung bezüglich des 'Olivin-Diallag-Gesteins' von Schriesheim im Odenwald," *Neues Jahrb.*, I (1885), 242.

[7] G. H. Williams, "The Peridotites of the 'Cortlandt Series' on the Hudson River Near Peekskill, New York," *Amer. Jour. Sci.*, XXXI (1886), p. 30, note.

[8] John W. Judd, "On the Tertiary and Older Peridotites of Scotland," *Quart. Jour. Geol. Soc.*, XLI (1885), 401–7.

[9] Raimund William Schäfer, "Der basische Gesteinszug von Ivrea im Gebiet des Mastallone-Thalles," *Tscherm. Min. Petr. Mitth.*, XVII (1897), 512–14.

[10] A. Sjögren, "Om förekomsten af Tabergs jernmalms fyndighet i Småland," *Fören. i Stockh. Förhandl.*, III (1876), 58.

EICHSTÄDT.[1] Valbellite consists of bronzite, olivine, and brown hornblende in variable amounts, with accessory magnetite, green spinel, and pyrrhotite. The magnetite may be very abundant. Olivinite covers a group of rocks of varying composition. Essentially they contain olivine with augite and hornblende. Anorthite may be present in some occurrences, but in general it is rare. Another rock belonging here is Saitzew's[2] hornblende-diallage-peridotite from the Koswinski-Kamenj, in the Urals, later described by Duparc and Pearce[3] under the name koswite. This rock consists of much diopside, less olivine and less hornblende in a cement of magnetite, giving a sideronitic texture. Chrome spinel is also present. The main characteristic is the texture, which, the authors say, passes to that of ordinary peridotite by a decrease in the amount of magnetite. The sideronitic texture is not confined to these dikes, but also occurs in other magnetite-rich peridotites.

Families 4 and 11.—This group includes the olivine-pyroxene (both orthorhombic and monoclinic) rocks. Among them are lherzolite DE LAMÉTHERIE,[4] named from the original locality of Lherz, in the Pyrenees, and consisting of olivine, enstatite, and diopside, with accessory picotite. In other localities the pyroxene is diopside and bronzite, and chromite may be present in small amounts.

Diallage-peridotite KLOOS[5] consists of diallage, olivine, and some chromite.

Wehrlite is a name given by von Kobell,[6] in 1834, to a rock from Wehrle in Hungary, under the impression that it was a mineral.

[1] Fr. Eichstädt, "Pyroxen och amfibolförande bergarter från mellersta och östra Småland," *Bihang till Kongl. Svenska Vetenskaps-Akademiens Handlingar*, XI, No. 14 (1887), pp. 95, 123.

[2] A. Saitzew, "Geologische Untersuchungen im Nikolai-Pawdinschen Kreise und Umgebung, im Gebiete des Central-Ural und dessen östlichen Abhang," *Mem. Com. Geol.*, XIII, No. 1 (1892), p. 91.

[3] L. Duparc and F. Pearce, "Sur la koswite, une novelle pyroxénite de l'Oural," *Comptes Rendus*, CXXXII (1901), 892–94.

[4] De Lamétherie, *Théorie de la terre*, II, 281; also *Leçons minéralogique*, II, 206.

[5] J. H. Kloos, "Über Uralit und die strukturellen Verschiedenheiten der Hornblende in einigen Gesteinen des Schwarz- und Odenwaldes," *58 Vers. deutsch. Naturf. u. Arze* (Strassburg, 1885); also "Studien im Granitgebiet des südl. Schwarzwaldes," *Neues Jahrb.*, III (1884), 146.

[6] Franz von Kobell, *Geschichte der Mineralogie* (München, 1864), p. 660.

The name is now generally applied to peridotites with olivine and much diallage or augite, although the type rock actually contains considerable hornblende and belongs to Family 3, 6, or 10.

Harzburgite ROSENBUSCH[1] and saxonite WADSWORTH[2] were applied to peridotites composed of olivine and a monoclinic pyroxene. Vogt,[3] following Brögger, uses saxonite for the iron-poor olivine-enstatite rocks and harzburgite for the iron-rich members. A saxonite from Minnesota, described by Hall,[4] consists of enstatite 60 per cent, olivine 35 per cent, and ores 5 per cent, consequently belongs to (4211).

Families 7 and 9.—These are the families of the olivine-free amphibole-(or biotite-)pyroxene rocks. Here belong Cromaltite SHAND,[5] consisting of aegirite-augite 51.9 per cent, melanite 15.6 per cent, biotite, apatite, and ores. Its number is (429). A hornblende-hypersthenite, named bahiaite by Washington,[6] with the percentages hypersthene 46, augite 5, hornblende 40.7, and ores 8.3 (rock number 429), also belongs here. Washington says olivine is negligible in bahiaite, but one such rock described by him[7] contains 7.5 per cent, which places it in Family 10.

Family 8.—This is the family of the amphibolites and hornblendites. Among these is a hornblendite from Brazil, described by Washington.[8] It consists of hornblende 91.6 per cent, olivine 3.6 per cent, and magnetite 5.1 per cent.

[1] H. Rosenbusch, *Mikroskopische Physiographie der massigen Gesteine* (2d ed.; Stuttgart, 1887), p. 269.

[2] M. E. Wadsworth, *Lithological Studies* (Cambridge, Mass., 1884).

[3] J. H. L. Vogt, "Beiträge zur genetischen Classification der durch magmatische Differentiationsprocesse und der durch Pneumatolyse entstandenen Erzvorkommen," *Zeitschr. f. prak. Geol.* (1894), p. 384, note.

[4] C. W. Hall, "The Gneisses, Gabbro-Schists, and Associated Rocks of Southwestern Minnesota," *U.S. Geol. Surv., Bull. 157* (1899), p. 111.

[5] S. J. Shand, "On Borolanite and Its Associates in Assynt," *Trans. Edinburgh eol. Soc.*, IX (1910), 394.

[6] Henry S. Washington, "The Charnockite Series of Igneous Rocks," *Amer. Jour. Sci.*, XLI (1916), 331–32.

[7] *Ibid.*, "An Occurrence of Pyroxenite and Hornblendite in Bahia, Brazil," *Amer. Jour. Sci.*, XXXVIII (1914), 86.

[8] *Ibid.*, p. 82.

Another rock belonging here is the biotite-pyroxenite from New Zealand described by Hutton.[1] It consists of biotite and hornblende in about equal proportions.

Family 12.—Finally, in Family 12, belong the pure pyroxene rocks, such as diallagite, bronzitite, hypersthenite (together called pyroxenolites by Lacroix).[2] Websterite WILLIAMS,[3] named from Webster, North Carolina, contains both orthorhombic and monoclinic pyroxenes with accessory iron ores.

Ilmenite-enstatitite VOGT[4] contains as much as 60 per cent ilmenite; consequently it ranges from Order 2 to 3. A magnetite-pyroxenite described by Jennings[5] and Bastin[6] also belongs to Order 3. It contains 67.25 per cent magnetite, 8.30 per cent ilmenite, 16.89 per cent diopside or augite, 6.70 per cent spinel, and .18 per cent apatite.

APPENDIX

This appendix might be introduced by the Spanish proverb: "El sabio muda consejo, el necio no," were there no danger of some critic replying with: "Prudentis est mutare consilium; stultus sicut luna mutator."

In the first instalment of this paper (p. 38), the writer spoke of a contemplated change by which seventy-two families were to be omitted, but letters sent to a considerable number of petrographers found no uniformity of opinion. Some were in favor

[1] F. W. Hutton, "On a Hornblende-Biotite Rock from Dusky Sound, New Zealand," *Quart. Jour. Geol. Soc.*, XLIV (1888), 745–46; also "The Eruptive Rocks of New Zealand," *Jour. and Proc. Roy. Soc. New South Wales*, XXIII (1889), Part I, p. 154.

[2] A. Lacroix, "Sur les roches basiques constituant des filons minces dans la lherzolite des Pyrénées," *Comptes Rendus*, CXX (1895), 752–55.

[3] George H. Williams "The Non-feldspathic Intrusive Rocks of Maryland and the Course of Their Alteration," *Amer. Geol.*, VI (1890), 40–41.

[4] J. H. L. Vogt, "Bildung von Erzlagerstätten durch Differentiationsprocesse in basischen Eruptivmagmata," *Zeitschr. f. prak. Geol.* (1893), p. 8.

[5] E. P. Jennings, "A Titaniferous Iron-Ore Deposit in Boulder County, Colorado," *Trans. Amer. Inst. Min. Eng.*, XLIV (1913), 14–25.

[6] Edson S. Bastin, "Economic Geology of Gilpin County and Adjacent Parts of Clear Creek and Boulder County, Colorado," *U.S. Geol. Surv., Prof. Paper 94* (1917), p. 47.

of dropping all the rocks of the monzonitic series, others of retaining all; some favored dropping the quartz-monzonites but not the monzonites, others dropping the monzonites but not the quartz-monzonites. During the past year, while the foregoing paper was awaiting its turn for publication and while going through the press, the writer collected and determined many more modes and found that the monzonitic group is unnecessary except possibly in the granite-granodiorite and syenite-diorite series. Now apparently the only monzonites which anyone desires to retain are those of these two groups. Consequently the writer believes the following changes will satisfy all sides.

All classes and orders are to be subdivided as stated on pages 38 to 40. Families are to be divided and numbered hereafter as shown in Figure 7 instead of as in Figure 4, the divisions

0
1 2 3 4
5 6 7 8
9 10 11 12

---

13 14 15 16
17 18 19 20
21 22 23 24
25

FIG. 7.—The new subdivisions for families

being at 0–5–50–95–100. In the case of the quartz-monzonites-granodiorites, and syenites-monzonites-monzodiorites (Families 7–8–9, and 12–13–14, Fig. 4), subdivisions *may* be introduced if desired with the 0–5–35–65–95–100 per cent limits as before. In such cases they will be numbered, to conform with the new family numbers, 5, 6′, 6′–7′, 7′, 8, 9, 10′, 10′–11′, 11′, 12. Therefore, for example:

226 is normal granite with the Kf-Plag ratio between 95–5 and 50–50.

2210 is normal syenite with the same Kf-Plag ratios.

227 is granodiorite as originally intended by Lindgren (p. 168 above) with the Kf-Plag ratio 50–50 to 5–95. (Family 237 is granogabbro.)

2211 is normal syenodiorite (2311 syenogabbro) with Kf-Plag ratio like the preceding.

For those who wish to use the monzonitic subfamilies:

226′ is more limited granite with the Kf-Plag ratio between 95–5 and 65–35. It may be called monzogranite.

2210′ is limited syenite with the same Kf-Plag ratios. It may be called monzosyenite.

226′–7′ is quartz-monzonite or adamellite, Kf-Plag ratios 65–35 to 35–65.

2210′–2211′ is monzonite, with same ratios as preceding.

227′ is limited granodiorite with Kf-Plag ratios between 35–65 and 5–95. Better called monzotonalite, leaving granodiorite for 227.

2211′ is monzodiorite, same ratios as preceding.

Thus petrographers who wish to use quartz-monzonite and monzonite have subfamilies at their disposal and these subfamilies may be carried through the whole system if desired. Normally only the families would be used.

So far as names are concerned, they remain as given in the preceding article except that Families 3, 8, 13, 18, 23, and 28 drop out entirely and the adjacent families (and their names) extend to the center line.

In Class 4 the subdivisions are to be made on the same divisions, therefore the left face of Figure 5 should be divided as the upper half of Figure 7 and the positions computed in the same manner as the families in the other classes.

In Part I, therefore, the following changes are to be made in the rules on pages 43 and 44.

Page 43, 3 lines from bottom, *omit* five.

Page 44, lines 7–8, *for* 0–5–35–65–95–100 *read* 0–5–50–95–100.

Page 44, lines 12–14, *for* the mineral of one corner, etc., to end of sentence, *read* olivine to the sum of the biopyriboles, and of biotite plus amphibole to pyroxene.

Another correction that should be made is on page 42, where zinnwaldite is to be taken away from the auxiliary constituents and added to the dark micas under mafites.

The principal advantage of the system as it now stands is in the rapidity with which a rock may be classified. It is much easier to determine whether the potash feldspar is greater or less in amount than the plagioclase than it is to estimate whether it falls between the 5–35–65–95 limits.

GEOLOGICAL SETTING OF NEW MEXICO

CHARLES KEYES
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The unique distinction which New Mexico holds in American geology is that it is the meeting-point of four major and diverse geographic provinces. Together these four provinces embraces nine-tenths of the North American continent. Effects of general land depletion under widely different climatic conditions are thus rarely so strongly contrasted.

Situated well within the boundaries of the vast southwestern desert, the operations of the epicene geologic processes are rendered the more conspicuous because of the fact that they are so very different from those of the pluvial eastern parts of the country with which most of us are most familiar.

New Mexico is distinctly a mountainous country. Its orogeny, however, is chiefly erosional rather than tectonic. Relief of the area is characteristically that of a land of little rain. Facial expression of the region is clearly not stream-corraded but wind-abraded. Owing to the fact that the wind sweeps up its chips as fast as it cuts them the magnitude of eolic erosion is at first difficult to measure with any great degree of satisfaction. Except under especially favorable conditions definite figures cannot always be given. Only when a desert chances to have, somewhere within its boundaries, remnants of old peneplains highly uplifted may the extent of regional depletion be closely estimated. As do moist lands under the influences of stream activities, so arid regions soon develop strong contrasts of surface relief under wind scour. Belts of weak rocks are soonest worn down, leaving the hard rock masses protruding as mountains

In a region of uniform flat-lying strata the relief contrasts are not always marked. When, however, there are rock beds of great thickness, alternating hard and soft members, with close-patterned mountain structures as in the arid lands of western United States,

differential relief effects attain maximum extremes. In this tract it is that the seeming youthfulness of the lofty desert mountains is at once impressed with amazing vividness upon the mind of the observer fresh from his pluvial homeland.

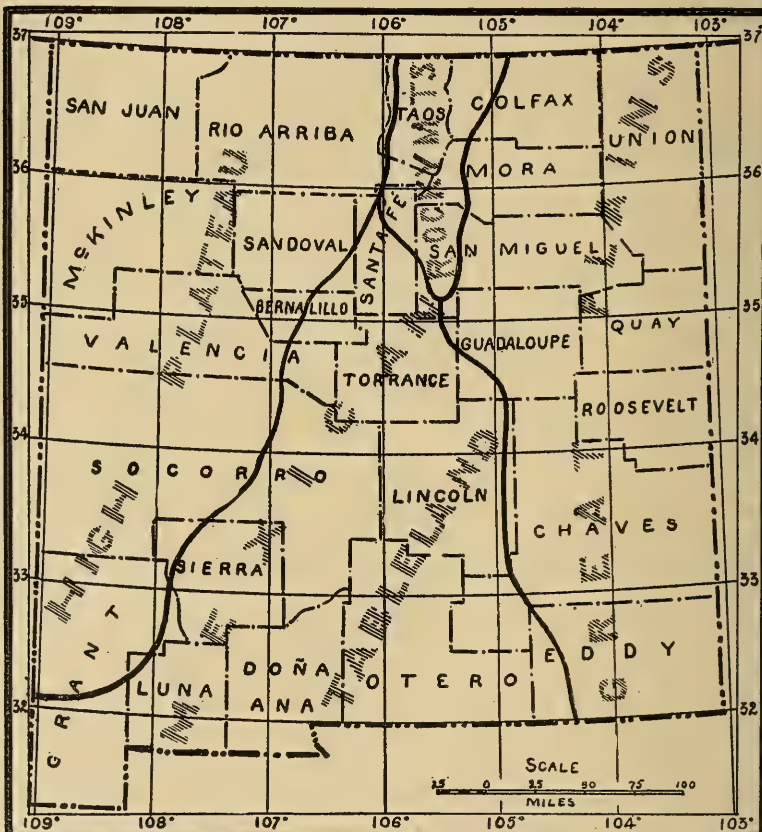

FIG. 1.—Physiographic regions of New Mexico

Once clearly discriminated, wind-graved relief expression is seldom mistaken for any other kind. Its individuality is very strong. Wind-beveled surfaces are smoother than water-formed plains possibly can be. The rock floors which characterize so many desert plains are phenomena as novel as they are unexpected.

Desert ranges rising abruptly out of the plains about impart characteristic form to the enisled landscape. The girdled mountain attests the vigor of natural sand-blast action; and its maximum effectiveness is at the plains line. Plateau plains of the desert manifestly represent former levels of the general plains surface. The notable absence of foothills around the mountain bases appears to be an idiosyncrasy of arid lands.

Arid planatation takes place uphill as well as down; antigravitational gradation is unknown where streams erode. High gradients of the intermontane plains and strong pitch of valley

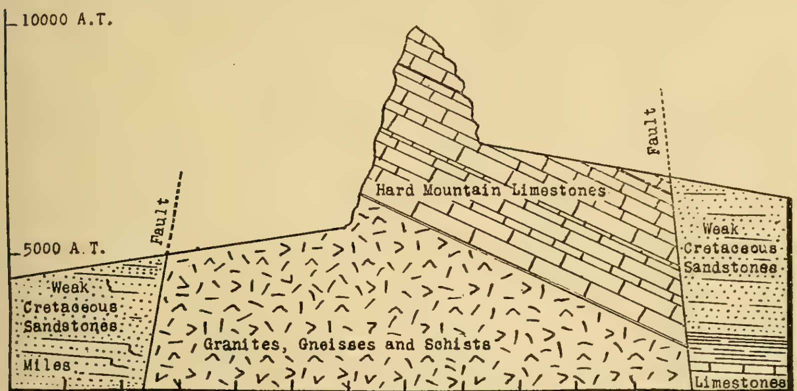

FIG. 2.—Sierra de los Caballos: origin of enisled relief

axes which are displayed on every hand are not possible in regions where water action is directly the reverse of plains forming. Of minor features attributable to wind abrasion in the lands of little rain, there are a multitude that have been ascribed to normal water corrasion but that are now known never to have been touched by stream. Upon all of these the wind marks when once pointed out are unmistakable.

It so happens that the broad arid tract of southwestern United States has within its borders abundant traces of former base-level plains, one of which peneplains is now raised more than two miles above sea-level. The attainment of its present position is regarded as having taken place in late Tertiary times. This great peneplain no doubt once extended over all of this desert region, at a level

somewhat above the tops of the present mountains. Inasmuch as desert conditions began to set in about the same time, there is every reason to believe that the magnitude of the general land depletion is represented by the difference between this old peneplain level and the present plains level—an interval of between 5,000 and 6,000 feet—or something over one mile of thickness, over an area equal to nearly one-quarter of that of the entire United States.

There are many considerations supporting the assumption that this area was before recent uplift a vast plain rather than a mountainous tract when arid climate was inaugurated. Inappreciable aid from stream corrasion in this prodigious regional depletion is indicated by the very fact of the prevalence of aridity itself. This region is one of the best extant, demonstrating beyond peradventure the almost boundless potency of the wind as an epicene power in re-forming the face of earth.

For general purposes of earth study no part of our land is so favored as New Mexico. More diverse phenomena are crowded together in limited space than perhaps anywhere else on our globe. Every known category of geologic process appears to be represented. Every known cause of geographic product seems to have been in operation. In great variety and with diagrammatic distinctness of textbook illustration are the larger rock structures displayed. Everything, too, is on such a gigantic scale. Such phenomena as dikes and faults have to be viewed from afar, from distances of miles, in order to get proper perspective of their relations. Orographic features, which are usually assumed to be structural, are found to be mainly erosional.

From the lofty cornice of the Sandias a landscape prospect spreads out a distance equal to that from New York to Chicago. Billows of mountain ridge take on an aspect of choppy sea as viewed from the deck of an ocean liner. The silver thread of the Rio Grande glints in the light of the desert sun for 400 miles until finally lost on the verge of the world—so clear is the dry, thin air of the desert.

The crystalline framework of the region is both varied and substantial. Crystalline schists of the fundamental complex are

abundant and of many colors. If he could have viewed them they would surely have gladdened the heart of Johannes Lehmann. Had the grand old pioneer in the field chanced to dwell in this country instead of Saxony the Erzgebirge might never have become so famous; and *Die Untersuchungen über Entstehung der altkrystallinischen Schiefergesteine* might have had the desert range of New Mexico for the central theme of his great epic.

The massive plutonic rocks, the granites, diorites, gabbros, and diabases, cut and intrude the pre-Cambrian complex in all directions. Their surface types appear to have utterly disappeared, probably during the long periods of erosion as indicated by the great unconformities.

Volcanics belong to all ages from the Cretaceous onward. San Mateo is one of the majestic volcanic piles of the continent. It now stands perched high upon a lofty Cretaceous pedestal. A forest of volcanic necks stretches away to the northward. Modern basalt flows cover hundreds of square miles. Older lava streams constitute the resistant cap of many plateau plains. Intrusive sheets run for scores of miles across the plains like great walls of cyclopean masonry. Laccolithes (Fig. 3) display their tectonic origin rather than formation through simple hydrostatic welling. Cinder cones are numerous (Fig. 4). Beside the fine cone of Capulin that of famed Vesuvius sinks into utter insignificance. The phenomena of classic Auvergne and the Phlegræan fields are reproduced again and again but on grander scale.

Stratigraphical succession in New Mexico is instructive to an extraordinary degree. It is, perhaps, the most complete to be found in any state in the Union. Curiously enough, above the pre-Cambrian crystalline complex highly resistant rocks compose the lower half of the geological column; while in strong contrast weak friable beds are segregated in the upper half. With a close-patterned orogeny this disposition has telling effect upon the final relief expression.

The geological column attains an enormous thickness. Archeozoic, Proterozoic, Paleozoic, Mesozoic, and Cenozoic sections are each about 10,000 feet in vertical measurement. Altogether there are 50,000 feet of strata reposing upon the non-clastic Azoics. It is

one of the great critical sections of the country. It is in reality the standard succession of the Western continent. It is a rock sequence such as James Hall vainly sought in his lifelong endeavor

Fig. 3.—Uncovered laccolith of Multiplex Ortiz

Fig. 4.—Zuni Salt Lake: birth of a volcano. Two cinder cones on floor of explosive crater, 600 feet deep.

to establish a standard stratigraphy for the world. It thrice transcends the united sections of Murchison, Sedgwick, and Lonsdale. With the depositional equivalents of its numerous hiatuses

it constitutes the longest and best sedimentative record of which we know.

Huge as is the sedimentative prospect, erosive depletion looms up in even vaster proportions. Thirty major unconformities stand for a very much longer interval of time than that which deposition occupied. Nowhere else on the face of the earth does it seem that the stratigraphic record is so clearly defined for a perfectly independent classification of geologic terranes according to diastrophic movement. It is the one place of all where orotaxial principles should sustain themselves under severest test. Any world-scheme of formational arrangement must stand or fall when fitted to this titan among rock sections.

That the pre-Cambrian rocks beyond the southern Rocky Mountains have never received the attention which they really merit recent disclosures amply attest. It seems possible that some day ere long they will divulge as clear a succession as did the transition rocks to English geologists a century ago. At least this is certainly the most promising field for new and large results that the American continent today offers in stratigraphy.

Three grand successions are presented. There is first at the top a thick section composed of relatively slightly metamorphosed and mildly deformed rock masses; then, in the middle, separated above and below, by a great erosional unconformity, a sequence of terranes highly altered, closely flexed, and repeatedly broken through by eruptives of various types; and third, at the bottom, an intensely metamorphosed and sheared complex in which no signs of classic origin are discernible. These grand successions are respectively Proterozic, Archeozoic, and Azoic.

To the Azoic basement are referred all of those lowest pre-Cambrian masses which, intensely altered and profoundly deformed, present no evidence of sedimentary origin. If any such classic character ever existed all trace is now completely obliterated. This intensely metamorphosed complex lying at the very bottom of the exposed rock column is a new find. Its discovery is yet too recent to enable its full significance to be properly evaluated.

Composing this fundamental complex are mainly thinly foliated gneisses, micaceous schists, squeezed granites, and other sheared

eruptives. The slightly altered granites, diorites, and diabases which cut the mass are manifestly relatively late intrusives.

Their evident enormous extent, their intensely metamorphosed condition, their extensive deformation, their sharp lithologic contrast with the superior metamorphics, and the marked erosional unconformity dividing the two successions all attest the supreme antiquity of the complex. The depositional equivalent of the summital unconformity may itself surpass in duration the stratigraphic record of the entire Paleozoic section. The best developments of the typical non-clastic Azoics are in the southwestern portions of the state.

The Archeozoic platform is bounded both above and below by marked erosional planes of unconformity. The rocks are all highly metamorphosed. The presence of quartzites, slates, and marbles indicates the clastic origin of a large part of the mass. The section is very thick, possibly not less than two miles.

In marked contrast with the inferior Azoic rocks are the evidences of a clastic origin of the major portion of the section, and a distinct lithologic sequence is plainly discernible. Unconformities which are associated may correspond to those shown in the Grand Canyon, but it is believed that some of the latter are superposed in New Mexico. It is really the Archeozoic rocks chiefly which heretofore have been called Archean, the Azoic masses not being recognized and the Proterozoic segregation not being differentiated.

A thick sequence of pre-Cambrian clastics which are only slightly altered is displayed in the Tijeras Canyon, in the Sandia Range east of Albuquerque, where in a sharp fold a mile of strata outcrops in continuous horizontal section. In discontinuous exposure at least another mile of beds is evidently present. The strata are chiefly shales, locally more or less indurated with some quartzite beds and intrusive granites.

The quartzite beds which stand at high angles are commonly mistaken for immense quartz reefs, and under such misconception they are extensively prospected for gold. Microscopical examination in thin slices demonstrates conclusively that the rock has a clastic origin, and that it is an old sandstone indurated by the

interstitial deposition of silica disposed in optical continuity with the separate sand grains. The enormous thickness of the shales is especially noteworthy. It is probable that eventually they will yield an extensive fauna, or a succession of faunas. Should the rock section prove fossiliferous the opportunity for determining faunal sequence would certainly be as favorable as among any Paleozoics of the continent.

Where the crest of the great Tijeras fold of the Proterozoics is deeply beveled off flat-lying limestones of latest Paleozoic age recline directly upon it. This notable unconformity plane represents a period of time of vast duration, one almost coextensive with the Paleozoic era. No less than ten great erosion intervals are superposed one upon another.

Although the early Paleozoic strata are entirely absent over the northern half of New Mexico they are extensively developed in the southern part of the state. There some of the major terranes were identified and correlated with the European sections almost as soon as they were in the Upper Mississippi Valley, or within a decade of the first appearance of Murchison's and Sedgwick's classic works.

When in 1874 undoubted Cambrian beds were first recognized by Jenney in New Mexico only unimportant sandstones were disclosed in the Franklin Mountains north of El Paso. Since that date the extent of the section has been greatly expanded, until now over 1,000 feet of sandstones, quartzites, and limestones are known. Westward these formations connect with the great Cambrian sections of Arizona.

As indicated by the contained fossils both mid- and late-Cambrian sections are fairly well represented, the former by about 700 feet of strata and the latter by 400 feet. There are no evidences of the presence of early Cambrian beds within the borders of the state, and it does not seem likely that any ever will be found.

Ordovician strata were the first Paleozoic rocks recognized within the limits of New Mexico. As early as 1848 Wislizenus recorded the finding of Ordovician (lower Silurian) fossils in rocks west of El Paso. A few years later both Shumard and Antisell

discovered similar organic remains in the mountains lying to the north of the same point. The section developed rapidly until it reached a thickness of more than 500 feet, extended entirely across the southern part of the state, and comprised three important series corresponding to the three subdivisions of the period.

These limestones are abundantly fossiliferous. The forms indicate the same sub-periodic divisions that are commonly recognized on the eastern side of the continent. Much of the bottom and top of the general section for the continent is missing in New Mexico. Between the Ordovician beds and the Cambrian below and the Silurian above marked unconformities prevail so that the first-mentioned unit is sharply defined.

Silurian sediments are poorly developed. The rocks out-crop in a thin broken line across the southwestern corner of the state. That deposition during the period was extensive in this region is quite manifest; but it is also evident that during Devonian and Mississippian times the deposits were largely removed through profound erosion. The contained fossils indicate only the Niagaran horizons of the standard eastern section.

From the character of the organic remains the presence of Devonian rocks in New Mexico receives early announcement. Both Antisell and Hall in 1856 call attention to the fossil evidence. Dutton's statement that Devonian strata were generally wanting in the eastern part of the Colorado High Plateau region is somewhat misleading. These rocks are really very much better represented in southwestern New Mexico than has been commonly supposed. In the vicinity of Santa Rita, in Grant County, are 400 feet of light-colored, fine-grained limestones and shales which carry abundant organic remains.

Two parts of Devonian time appear to be represented. The basal shales seem to belong to the mid-Devonian section; while the limestones are late Devonian in age. A surprising feature is that the fauna is the typical Lime Creek phase of northern Iowa. This horizon corresponds to the uppermost part of the section represented in the Upper Mississippi Valley, which is, according to Tschernyschew, Williams, and others, who have given the subject most attention, mid-Devonian in age. These authorities also

agree on the appearance of the fauna in the West, or Mississippi Valley region, much earlier than in the East, or New York province; so that, although its age in the first-named locality is strictly mid-Devonian, in the second locality it is late Devonian. This being the case, the same migratory fauna may have put in an appearance in the southwestern or New Mexican province, considerably earlier even than it did in the Upper Mississippi Valley region—possibly in the middle or latter part of early Devonian time.

The Mississippian succession in New Mexico comprises only a limited portion of the middle division of the Mississippi Valley section. Both the upper, or Tennesseean, and the lower, or Waverleyan divisions seem to be entirely missing. Because of its restricted representation and its other notable peculiarities the southwestern sequence is designated the Socorran series. The maximum thickness of these rocks is about 400 feet.

Both the Chouteau and Burlington faunas of the Mississippi Valley are well represented. The list of organic remains is almost as extensive as that of the type localities. Fossils from the Modoc limestone, which extends eastward from Arizona, indicate higher horizons, probably so high as the Keokuk level. Curiously, the huge gastropods which are so rare in the East are very abundant in the Southwest.

The especial importance of the New Mexican section of the Mississippian rocks is that it directly connects the eastern or Ozark sequence with that of the Far West. Summing up the evidence regarding these strata as they are represented around the border of the Colorado High Plateau it appears that there is in the Southeast and South, in southwestern New Mexico and eastern Arizona, the Socorran series; in the West, in northwestern Arizona, the Lower Red Wall formation; in southwestern Colorado the Ouray (upper part) limestone; and east of the southern Rocky Mountains the Millsap limestone. In New Mexico the succession is probably most completely represented and most varied, although perhaps not including all that is represented in Colorado.

In strong contrast with the Pennsylvanian sequence of the middle and eastern portions of the continent the southwestern succession is almost unbrokenly calcareous. A single plate of

limestone, which extends over the entire area of the state, reaches far into Texas on the one hand, and on the other hand completely over the Colorado dome to the Grand Canyon, where it appears as the Aubrey limestone, has in New Mexico a thickness of 5,000 feet.

These unbroken limestones are the open-sea analogues of the coastal coal measures of the Mississippi Valley. Where in Iowa they are mainly represented by a great erosional interval, and in Arkansas by 20,000 feet of shore deposits, in the New Mexican field coal-bearing measures are all but completely vanquished. Something of the enormous Arkansan series seems to find expression in the diminutive Ladronesian series with its bare 200 feet of Alamito shales and a scant foot of coal. The last-mentioned formation, which no doubt was once one of very considerable magnitude, is almost effaced through erosion which took place before the laying down of the limestones, which in marked unconformity rest directly upon these shales.

Pennsylvanian, or upper Carboniferous, limestones attain a thickness of 2,000 feet in northern New Mexico. There they recline directly upon the surface of the old pre-Cambrian basement, all else of the Paleozoics being absent. In the South, where they reach a measurement of upward of 5,000 feet and are known as the Hueco succession of limestones, they repose successively upon Mississippian, Devonian, Silurian, Ordovician, and Cambrian formations.

In the North the great limestone plate is best known in the lofty Sandia and Manzano ranges, east of Albuquerque. Throughout this district it appears to be broadly separable into two strongly contrasted formations—a lower shaly and black limestone, and an upper member comprising chiefly massive blue and gray limestones. To the inferior member, 1,000 feet thick, the title "Lunasian series" is given. To the upper sequence, also about 1,000 feet in thickness, the term "Maderan series" seems most appropriate.

On the basis of the determined faunal characteristics the stratigraphical position of the Lunasian series appears to correspond nearly with that of the Missourian series of the Mississippi Valley. Upon the same grounds the Maderan series is paralleled

with the Oklahoman series of the eastern field, but which some Kansas workers are prone to correlate with the far-off Permian rocks of the Russian Urals (Fig. 5).

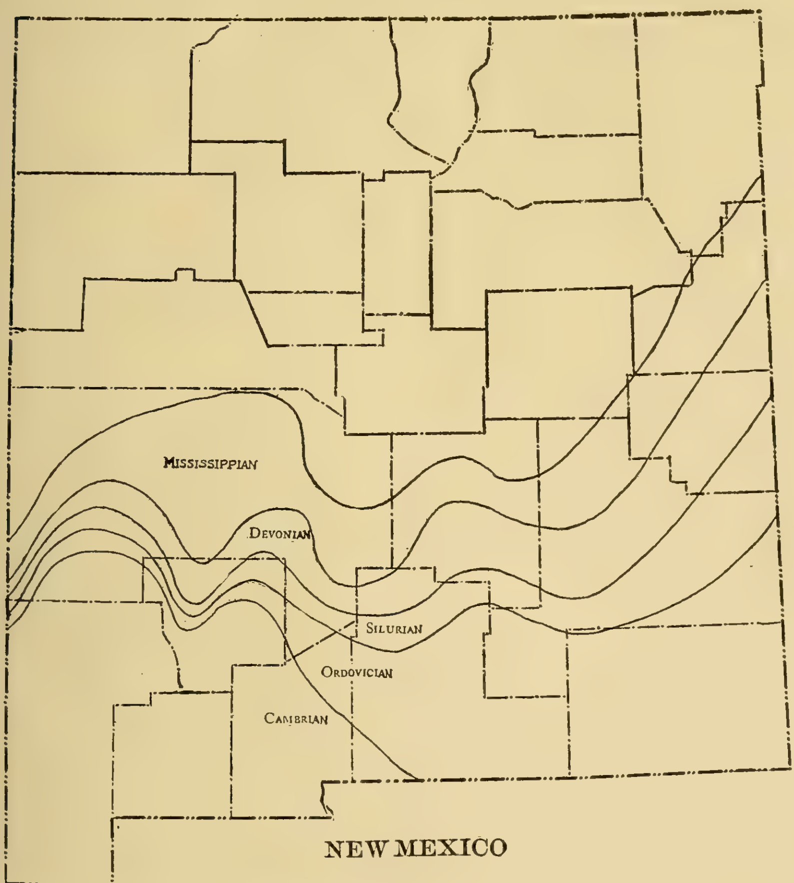

FIG. 5.—Areal range of periodic formations

As Pennsylvanian time was ushered in with the deposition of sands and clays, so also did it close. Succeeding the huge limestone plate is the Bernalillan series of "Red Beds." As first pointed out in 1904[1] the "Red Beds" problem which so long had baffled

[1] *Report of the Governor of New Mexico to the Secretary of the Interior for 1903*, p. 339 (Washington, 1904).

geologists found a ready solution in the discovery that these deposits were not accumulations of a single geologic age, but, in their different parts, of three distinct ages. Beds of similar lithologic aspect of Pennsylvanian, Permian, and Triassic ages were directly superposed, the normally intervening formations being absent. This was, then, the real explanation why different investigators in different localities had determined such diverse dates for their several sections. Even the unconformity planes were overlooked.

The recognition of "Red Beds" of Pennsylvanian age was a distinct advance in the stratigraphy of the Southwest.

It is a curious travesty on the fates that despite the acrimonious controversy which waged for more than a full generation over the possible presence of Permian beds in America, the one section which would have most speedily ended it remained unnoticed, albeit its fossils had long been fully made known. As early as 1860 Shumard described what he distinctly designated a Permian fauna from the Sierra Guadalupe on the New Mexico–Texas boundary; but its true significance remained in complete obscurity for half a century, when Girty accidentally pointed out its global relationships.

Although the Guadalupan succession of sandstones and limestones is nearly 4,000 feet thick at the typical locality the formation rapidly diminishes in force to the northward. Before the Sandias are reached the Bernalillan "Red Beds" and the Cimarronian "Red Beds" are brought together to form an uninterrupted "Red Beds" section.

Cimarronian "Red Beds" clothe the backslope of the Guadalupe Mountains and extend northeastward far into Kansas. There, and through the Panhandle of Texas, they are in turn overlaid by Triassic "Red Beds." The fact that a marked erosional unconformity separates the two terranes is a recent observation. To the northwest similar merging of "Red Beds" in continuous sequence obtains; and the Triassic Doloresian formation immediately succeeds Cimarronian deposits.

In New Mexico the strata of Triassic age are predominantly typical "Red Beds." There are two series of red shales and sand-

stones separated by an erosion interval. The earlier of the two series is confined to the east side of the Rockies, while the later one is represented chiefly on the west side of the Cordillera. Their total thickness is nearly 2,000 feet.

Like the Triassic sediments the Jurassic succession comprises an earlier and a later series, set off from each other by a great erosional unconformity. Together they represent a column 1,200 feet thick. The Morrisonian series is chiefly composed of argillaceous deposits. Of these the Chaquaqua (Chicago) shales occupy one-half of the entire section. They are underlaid by a basal sandstone. A notable erosion unconformity separates them from the succeeding Comanchan deposits.

When in the early fifties of the last century Jules Marcou, colleague and exiled compatriot of Louis Agassiz, fresh from the Jura Mountains, introduced into this country the European title "Jurassic" it was the Tucumcari section in eastern New Mexico that was involved. Around this Cerro Tucumcari raged a storm center for a full generation. After being overborne by sheer weight of numbers and after being submerged for seventy-five years Marcou finally comes into his own. Cerro Tucumcari proves to contain the full Jurassic section of the region. Marcou erred only in including some of the Dakotan sandstone layers.

The important Comanchan succession of Texas and the Gulf region finds but feeble representation in New Mexico, and then only as an attenuated border which soon vanishes completely against the Cordilleran uplift. The basal limestones of Texas are traceable around the Llano Estacado. The shales extend farther. Erosional unconformity separates its two series, and like sedimental breaks mark both top and bottom of the sequence. Because of the fact that the thin shale beds are immediately under the massive Dakotan sandstone they usually escape notice.

The basal Dakotan sandstone of the Cretaceous succession is especially noteworthy by reason of its very wide geographical distribution. In the Rocky Mountain region it is further remarkable because of its disposition on an old peneplain surface, which, although much deformed, now coincides with the tops of the highest peaks. Where the southern Rockies plunge in a triple fold

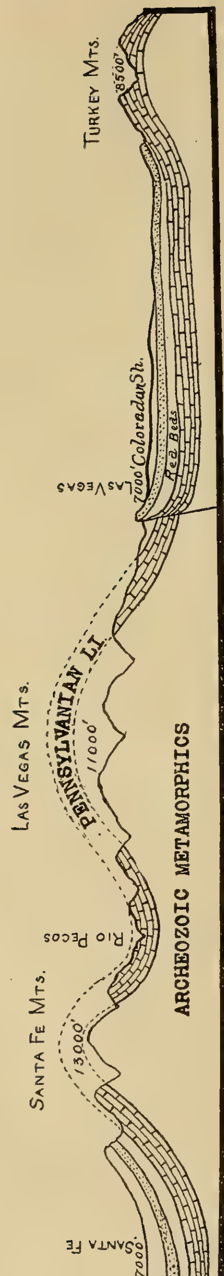

Fig. 6.—Ceja Glorietta: end of the Rocky Mountains

beneath the general plains' surface of the Mexican table-land the Dakotan sandstone forms a magnificent inward-facing escarpment. Along the steep interior face the Atchison, Topeka, & Santa Fe Railroad skirts for a distance of fifty miles. There, as elsewhere on the continent, the Dakotan sandstone is one of the geological landmarks of the region. With a thickness of 300 feet it is, perhaps, the most extensive basal sandstone of which we know (Fig. 6).

Immediately following the Dakotan sandstone is a fine succession of marine shales and limestones, which in New Mexico have a thickness of upward of 2,000 feet. This is the Coloradan series. A quite unusual feature is that the series preserves its subdivisional integrity through a distance of 1,000 miles, to Iowa and Minnesota, on the far side of the Continental Interior basin.

A succeeding 2,000 feet of strata comprising sandstones and shales constitute the Montanan series. It is an important coal-bearing formation, containing a larger fuel supply than do the coal measures of the entire Mississippi Valley. In early accounts of the region these coals were all regarded as Laramian in age. Locally the coal seams overlying the Ortiz laccolith are changed into high-grade anthracite, the quality of which compares favorably with the best hard coals of the Appalachians. East of the Rockies the Montanan beds merge into the marine Pierre shales.

As the uppermost member of the Cretaceous section the Laramian series embraces only a small part of the beds formerly paraded under this title. By divesting the old Laramie section of that portion which is really Tertiary in age the long drawn-out controversy concerning the true age of these beds comes to an abrupt end.

With the principal coal beds referred to the Montanan series below and the Ratonan series above the so-called Laramie formation of New Mexico becomes almost as barren as the marine Coloradan series. Still, in the northwestern part of the state, the Pictured Cliffs sanstones and the Navajo shales attain a thickness of nearly 1,200 feet.

Tertiary sedimentation in the New Mexican area begins with beds the deposition of which seem long to antedate the earliest Eocene formations of other parts of the world. When in the course of coal investigations in 1906 a marked erosional unconformity and basal conglomerate were found in the lofty Raton Mesa about 1,500 feet below its massive lava cap, it was surmised that the solution of the Laramie problem had been stumbled upon and that above the erosion plane the beds were really Tertiary in age, while those beneath that line were Cretaceous. These conclusions were fully substantiated a decade later by Lee in an elaborate monograph on the geology of the region.

The Ratonan series is, then, older than the oldest Eocene deposits of the state, the Puerco beds, which, since the days of Cope in the region, were believed to be the earliest Tertiaries extant. It is an important coal-bearing section, which fact probably largely accounts for its early confusion with the original Laramie coal formations of the more northern Rocky Mountains districts. The erosion plane upon which the Ratonan sediments rest is a peneplain of wide proportions evidently worn down on the entire southern Rocky Mountains province. In its production no less than a mile of rock was removed.

The Aztecan series is represented by a basal conglomerate of very considerable thickness. Beyond the borders of the state the Arculeta conglomerate is succeeded by shales. No sediments are correlated with the erosional interval below. It is possible that

the basal unconformity is coextensive with the one beneath the Ratonan series on the opposite side of the Rockies, in which case the Arculeta and Maya formations are homotaxial. The term "Animas," which is sometimes applied to the beds of the San Juan basin is preoccupied.

In the Nacimientan series are included the basal beds of the old Wasatch group. It is regarded as earliest Eocene. It is subdivided into the Puerco clays and the Torrejon marls and sandstones. The deposits are doubtless entirely epeirotic in character and perhaps eolian. There is a large and varied vertebrate fauna. The outcrop constituted one of Cope's favorite collecting grounds. The beds have a maximum vertical measurement of 1,000 feet. Marked erosional unconformities separate all of the Tertiary terranes of the San Juan basin.

The Chaman series comprises the main body of clays, sands, and shales of the San Juan Wasatch succession. Canyon Largo sandstone is Newberry's early designation. Chaco terrane covers the principal clay deposits. Together they are nearly 2,000 feet thick.

Of manifest later date are the Tertiaries of the Rio Grande basin. These consist of the Galesteo sands and the Santa Fe marls, 1,300 feet in thickness. Over the Llano Estacado the latest Tertiary sands, 300 feet thick, are assigned to the Pecosian series.

The terranal names applied to the New Mexican Tertiaries cover only the main bodies of deposits. No doubt other titles will eventually be attached to the numerous minor members.

Quaternary deposits of New Mexico are chiefly desert concentrates. They are not mainly deflated materials, but accumulations left behind after the main bulk of fine rock débris has been sorted out and exported. The deflated dusts come to rest far outside of the arid region. Gravel and bowlder trains are principally the results of arroyo wash. Till-like materials are brought down from the highlands. Some glacial till yet remains on the sides of the highest mountains where ice fields were once feebly represented. Adobe soil is deflated dust temporarily at rest. Some fluviatile deposits are present. Lacustrine beds are rare, very limited, and quite ephemeral.

In the accompanying chart of New Mexican terranes the latter are fitted to the Chamberlin and Salisbury classification.

GENERAL GEOLOGICAL SECTION OF NEW MEXICO

Eras	Periods	Series	Terranes	Thickness in Feet	Rocks
	Present	Jornadan.....	....	25	Adobe
	Pleistocene ...	Palomasan....	....	200	Till
		Gilan........	....	250	Gravels
			Interval......	....	Unconformity
	Pliocene......	Pecosian......	Llano E......	300	Sands
			Interval......	....	Unconformity
	Miocene......	Arriban......	Santa Fe..... Galesteo......	500 800	Clays Sands
			Interval......	....	Unconformity
Cenozoic	Oligocene	Chaman......	Chaco........ Canyon L....	1,000 700	Clays Sandstones
			Interval......	....	Unconformity
	Eocene.......	Nacimientan..	Torrejon.....	300	Marls
			Interval......	....	Unconformity
			Puerco.......	500	Clays
			Interval......	....	Unconformity
		Aztecan......	Archuleta.....	250	Conglomerate
			Interval......	Great	Unconformity
	Arapahoe.....	Ratonan.....	Maxwell...... Houten...... Maya........	800 600 100	Shales Sandstones Conglomerate
			Interval......	Great	Unconformity
	Cretaceous....	Laramian.....	Navajo....... Pictured Cl...	1,000 150	Shales Sandstones
			Interval......	....	Unconformity
Mesozoic		Montanan....	Lewis........ Chacra....... Mesa Verde... Pina Vititos...	600 200 800 250	Shales Sandstones Shales Sandstones
			Interval......	....	Unconformity
		Coloradan....	La Jara...... Apishapa..... Timpas...... Gallinas......	1,000 500 300 200	Shales Shales Limestones Shales
		Dakotan......	Glorietta.....	300	Sandstones
			Interval......	Great	Unconformity

GENERAL GEOLOGICAL SECTION OF NEW MEXICO—*Continued*

Eras	Periods	Series	Terranes	Thickness in Feet	Rocks
Mesozoic	Comanchan		Kiowa	100	Shales
			Garrett	50	Conglomerate
			Interval	....	Unconformity
			Washita	500	Limestones
			Fredericksburg	200	Limestones
	Jurassic	....	Interval	....	Unconformity
		Morrisonian	Chaquaqua	150	Shales
			Travester	100	Shales
			Exter	75	Sandstones
		....	Interval	....	Unconformity
		Zunian	McElmo	300	Shales
			La Plata	300	Sandstones
	Triassic	Doloresian	Wingate	900	Sandstones
			Le Roux	800	Shales
			Shinarump	600	Conglomerate
		....	Interval	....	Unconformity
		Dockuman	Trujillo	300	Shales
			Tecovas	200	Shales
			Interval	....	Unconformity
Paleozoic	Permian	Cimarronian	Quarterm	150	Shales
			Greer	125	Shales
			Chaves	425	Shales
			Interval	....	Unconformity
		Guadaloupan	Capitan	2,500	Limestones
			Eddy	1,000	Sandstones
			Interval	....	Unconformity
		Bernalillan	Torrance	500	Shales
			Yeso	600	Shales
			Manzano	500	Sandstones
			Interval	....	Unconformity
		Maderan	Tellera	300	Limestones
			Gallegos	100	Sandstones
			Antonito	200	Limestones
	Pennsylvanian	Lunasan	Mosca	200	Limestones
			Coyote	75	Sandstones
			Montosa	400	Limestones
			Sandia	250	Shales
			Interval	Great	Unconformity
		Ladronesian	Alamito	200	Shales

GENERAL GEOLOGICAL SECTION OF NEW MEXICO—*Continued*

Eras	Periods	Series	Terranes	Thickness in Feet	Rocks
Paleozoic	Mississippian..	Tennessean...	Interval......	Great	Unconformity
		Socorran.....	Modoc........	200	Limestones
			Sierra........	50	Limestones
			Lake Valley..	150	Limestones
			Grande.......	25	Limestones
		Waverlyan....	Interval......	Great	Unconformity
	Devonian.....	Martinian....	Berenda......	50	Limestones
			Interval......	....	Unconformity
		Perchan......	Bella..........	250	Shales
			Silver........	200	Shales
			Interval......	....	Unconformity
	Silurian......	Santa Ritan...	Interval	....	Wanting
			Naiad........	250	Limestones
			Cibola.......	175	Limestones
			Interval......	....	Unconformity
Paleozoic	Ordovician....	Mimbresian...	Cristobal.....	165	Limestones
		Montoyan....	Frondosa.....	100	Limestones
		El Pasan.....	Armendaris...	300	Limestones
			Interval......	....	Unconformity
	Cambrian....	Chiricahuan...	Lone.........	300	Quartzites
		Chloridian....	Carrasco.....	75	Limestones
		Dragoonan...	Burro........	500	Quartzites
			Hawkins......	50	Limestones
			Mangas......	100	Quartzites
			Interval......	Great	Unconformity
Proterozoic	Superorian....	Valencian.....	Graphic......	1,000	Lavas
			Sandoval.....	....	Granites
			Interval......	Great	Unconformity
	Seikirkian....	Albuquerquan.	Ysidro.......	1,500	Shales
			Tijeras.......	250	Quartzites
			Interval......	....	Unconformity
		Garnuan	Antonio......	2,000	Shales
	Anian		Interval......	Great	Unconformity

GENERAL GEOLOGICAL SECTION OF NEW MEXICO—*Continued*

Eras	Periods	Series	Terranes	Thickness in Feet	Rocks
ARCHEOZOIC		Pecurisan	Truchas Penasco Serna	900 400 1,500	Slates Quartzites Schists
			Interval	Great	Unconformity
		Taosan	Solitario Rociada Sapello Ninos	800 250 300 1,000	Slates Limestones Quartzites Schists
			Interval	Great	Unconformity
AZOIC	....	....	....	....	Slates Gneisses Schists

For general completeness the New Mexican rock-pile stands *facile princeps* among American geological sections. Being at once both a critical and a standard terranal succession for the continent, it merits and invites closest inspection, carefulest evaluation, and widest comparison. It reflects regional crustal movements along a primitive continental plait more directly and more perfectly than perhaps any other known section. Amplitude of diastrophic oscillation is sufficiently large and sharp to make this a direct basis of genetic taxonomy. It admits of orotaxial classification of geological formations at its best.

MOVEMENTS IN CRYSTALLIZING MAGMA

FRANK F. GROUT
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The study of the crystallization of silicate melts has led to many important conclusions regarding igneous magmas, several of which are stated in papers recently issued from the Geophysical Laboratory with the authority of actual experience behind them. Where facts have been discovered, however, concerning a particular hypothesis there has been a tendency to minimize the probability of some other quite independent hypotheses and to carry the conclusions along into regions not covered by experimental data. In several papers since the publication of Bowen's important outline of the evolution of igneous rocks[1] the present writer has endeavored to reopen consideration of some hypotheses lightly brushed aside in that paper. The arguments have brought forth some new light, but much still remains to be done.

Liquid magma is known to move as it is intruded, and by convection. Crystallizing magma (to accept a usage that seems to be approved) is also known to be moved by intrusion and convection, and there are molecular movements by diffusion; in addition there are probably differential movements as crystals settle or float out of magma, and there may possibly be a straining or filter-pressing away from crystals. The magnitude of diffusion is pretty definitely settled by Bowen.[2] Little question has arisen over the movements of intrusion, but there is still question as to (1) the activity of convection at depth, (2) the effectiveness of crystal settling, (3) the mechanics and effects of filter-pressing.

[1] N. L. Bowen, "The Later Stages of the Evolution of Igneous Rocks," *Jour. Geol.*, XXIII, Supplement, November-December, 1915.

[2] N. L. Bowen, "Diffusion in Silicate Melts," *Bull. Geol. Soc. Amer.*, XXVII, p. 48.

CONVECTION

In making an estimate of the rapidity of convection[1] an argument was built up by starting with a variety of assumptions. This was done because several writers had assumed, without any suggestion of calculation, that the magma was too viscous to circulate. The value of assumptions not based on quantitative data may be illustrated by references to the effects of viscosity. Harker approves diffusion, but considers the magma too viscous to allow settling of crystals. Daly approves settling, but considers the magma too viscous to allow convection. Pirsson approves convection, but considers the magma too viscous to allow diffusion. Thus we get around the circle and all processes are still worthy of consideration.

The results of calculation, in actual figures, indicate great probability of some circulation. The calculated rates are not to be taken as at all accurate. Neither is it important to distinguish whether cooling, gas phase, or crystal phase is the dominant cause.[2] The evidences are sufficient to indicate some active circulation. Bowen says now that he has never doubted the reality of convection in magmas.[3]

The contrast presented in a paragraph headed "Crystal Settling vs. Convection" is apparently misleading. The present writer had no thought of differentiation except through the agency of crystallization. Convection seemed a necessary factor in explaining the combination of banded and fluxion structures. It is argued that the rhythm of settling would give the same banding as rhythm

[1] Frank F. Grout, "Two-Phase Convection in Igneous Magmas," *Jour. Geol.*, XXVI (1918), pp. 481–89.

[2] Bowen in a later paper questions whether the two-phase idea can be extended to aggregates of crystal and liquid. Let him try it. Simply suspend crystals in side of dish and release. His own reference to heavy liquid separations indicates that he has had experience with an operation in which two-phase convection is very common.

[3] N. L. Bowen, "Crystallization-Differentiation in Igneous Magmas," *Jour. Geol.*, XXVII, p. 412. One would certainly infer a doubt from the statement in the earlier paper, p. 12: "The same objections apply to the supposed maintenance of approximate uniformity . . . . through the agency of convection currents. . . . ." Certainly convection would *tend* to keep the composition uniform, and one would infer that since the magma does not remain uniform he saw no evidence of convection.

in currents. To this there is no question at all. But, in addition to banding, the Duluth rocks show an *orientation*. The combination is explained only by circulation.

Convection, as a general stirring, may be supposed to interfere with crystal settling. Probably in one sense this is true, for any liquid containing sediments clears more rapidly if left quiet. But the arguments for a circulation at Duluth are conclusive and have not been answered. Settling, if it occurred at all (and it probably did), occurred during circulation. Since the calculated rates of motion indicated that convection was more rapid than settling,[1] it is clear that convection might aid in bringing a crystal formed at the top of a magma chamber to some point near the bottom. Then as the current moved along the floor there might be settling enough to cause the growth of a rock layer at the bottom. Settling, however, is not the only process by which rock may grow. Simple cooling makes the shell of solidified wall or floor increase in thickness. The bottom layer of the moving current may become part of the floor by cooling and increasing in viscosity as well as by settling. Thus it may happen that even when circulation tends to prevent settling some settling may occur, and certainly some rock may accumulate along the floor.

In order to "make a case" for convection certain complications in the process were omitted in the original paper.[2] No doubt convection is far from a simple motion in large sheetlike chambers. There are the irregularities in the banding of most banded igneous rocks to prove the complexity of motion. There may even have been an approach to the theoretical hexagonal cells[3] of circulation. These, however, would have little effect on the result. No crystals would deposit on the sides of a cell—there is no support on the walls of such cells. Deposition would occur in bands on the bottom, almost as if the circulation was the simple case described.

[1] Frank F. Grout, *op. cit.*, p. 494.

[2] Unfortunately an error occurs in the copy of the calculation for gas-phase convection, *op. cit.*, p. 491: "lbs. per sq. inch" should be *atmospheres*. It seems correct values were used in calculation, but stated wrongly in copying.

[3] See *Jour. Geol.*, XXIV, pp. 219 ff.

CRYSTAL SETTLING

The reality of the separation of crystals from liquid magma by gravity has been clearly shown.[1] In crucibles a few centimeters deep, crystals formed and settled and grew to considerable size.

In order to determine equilibrium relations, efforts were made in the laboratory work to maintain uniform conditions of heat through the whole melt. Contrasted with these conditions are the large size and irregular cooling of intruded magmas. A temperature variation of 100° C. is not unlikely in the viscous liquid beginning to crystallize. If crystals form in a cooling top layer and settle to a hot interior layer they remelt and make the magma heterogeneous. Eventually the continued settling of crystals may so cool the central part of the magma that the crystals formed near the top settle through the central part without either growth or solution. It would take so long for this balance to be attained, however, that it seems likely that the roof phase would grow as a solid before many crystals settled. Meanwhile in any large mass the cooling sides of the chamber would start convection and entirely modify the situation. The probability seems to be that chambers a few feet thick are chilled; up to 100 feet crystal settling may be the dominant effect, but in larger chambers convection stirs things up too much. Settling a few feet removes crystals from the circulating magma.

The condition of the gabbro at Duluth was taken as a sign that no great amount of settling occurred,[2] and Bowen agrees that simple settling does not adequately explain the series of rocks developed. He finds it possible still to refer to the peridotites as a result of settling. They are bands, like other bands in the gabbro, and if most of the bands are not the result of settling it seems inadvisable to select the peridotites to support the original idea.

In a remark on the banded structure at Duluth, Bowen says that if crystallization is rhythmic, crystals brought down to the bottom by settling would result in precisely the same alternation as

[1] N. L. Bowen, "Crystallization Differentiation in Silicate Melts," *Amer. Jour. Sci.*, XXXIX (1915), p. 186.

[1] Frank F. Grout, "A Type of Igneous Differentiation," *Jour. Geol.*, XXVI (1918), p. 639.

if brought down by convection. In this he is wholly correct and no advantage is claimed for convection. It is only when the banding is accompanied by an orientation of grain that the evidence is strong against crystal settling. It is not the banding nor the parallelism which determines the process, but the combination of bands with a foliated structure. This was emphasized in the original papers.[1] As there stated, crystal settling is to be thought of as a matter of a few feet, not thousands of feet.

FILTER-PRESSING

A process of expulsion of residual fluid magma from a mass after a large proportion of the material had crystallized is advocated by Bowen and Harker. Preliminary suggestions of the idea are credited by Harker to Barrow and to Judd (who refer also to Osann, Teall, and Geikie).

In tracing these earlier statements of the idea, no good outline of the mechanics or general results could be found. Teall and Osann and Harker[2] describe patches of glassy or residual magma filling steam cavities when the gas of the cavity has been absorbed or condensed, or has escaped. No one can question the occurrence of rounded lumps formed from magma, but the source of the lumps and the process by which they got there, and the ultimate removal of any gas that may have been there, are hard to understand. If the magma was liquid enough to "ooze out from among the crystals" the gas just separated from the magma could hardly be absorbed, condensed, or allowed to escape, leaving a spherical hole. Barrow[3] has described a pegmatitic separation from granite, as have many others. In many cases this may be a process of separation of liquid from partly crystalline magma, but pegmatites are most readily explained by the readier penetration of thinly fluid *emanations* in advance of viscous magma. This is more nearly analogous to immiscible separation than to filter-pressing. Filter-pressing

[1] Frank F. Grout, "Internal Structures of Igneous Rocks," *Jour. Geol.*, XXVI (1918), p. 455.

[2] A. Harker, *The Natural History of Igneous Rocks*, pp. 324–25. Macmillan, 1909.

[3] George Barrow, "On Certain Gneisses and Their Relation to Pegmatites," *Geol. Mag.*, 1892, pp. 64–65.

involves differential pressures, and no such pressures are evidenced by the great majority of granites having pegmatitic facies. Barrow also refers to a case of straining off of magma into crevices too small for crystals to get in. Such an action is easily understood but would not be expected to produce large bodies of rock. Barrow goes on to say, however, that "the continuance of the pressure will still further force the liquid from the solid crystals, leaving at last just sufficient of the magma to fill the interstices between them." This can hardly be considered a clear outline of what happens "further" than the oozing of magma into cracks too small for the crystals to enter. Judd[1] has described andesite and pitchstone intrusions which he thinks separated by a process of "liquation"—apparently a growth of crystals along the walls leaving a residue of different composition. Harker, referring to the suggestion, says "it is easy to conceive of various modes of liquation and decantation, straining and filtration by which a partial separation may be brought about." Bowen has shown the improbability of diffusion sufficient to yield much differentiation by any liquation in this sense. "Decantation" is not a process of filter-pressing. To the present writer "straining and filtration" of a magma on any large scale are not easily conceived.

Harker reviews these descriptions, emphasizing the case of pegmatites and that of pitchstones related to andesites. He does not refer to any indication of a process of compression except in the case of numerous small pegmatite intrusions related to large granite gneisses. Even here the larger masses of pegmatite are better explained by a separation of some other sort.

Bowen presents the latest development of ideas on filter-pressing.[2] His first analogy is to the squeezing out of water from sand on a wet beach. There is little question that such a mesh of crystals as he suggests, up to 80 per cent of the total mass, might, when subject to differential pressure, give way and result in closer packing.

The supposed filter effects are described for three different cases, but no mention is made of the case of pegmatitic separation sug-

[1] J. W. Judd, *Quart. Jour. Geol. Soc.*, XLVI (1890), p. 379.

[2] N. L. Bowen, "Crystallization-Differentiation in Igneous Magmas," *Jour. Geol.*, XXVII (1919), p. 393.

gested by Barrow. First, horizontal compression of a laccolith, crystallized to about 80 per cent, might yield an upper differentiate of liquid;[1] the effect on the crystallizing residue is clearly described as follows: "The horizontal dimensions are shortened in consequence of closer packing of crystals." Second, horizontal compression of a sheet in which the top and bottom had partly crystallized might result in a squeezing of the liquid into the central zone; here again the crystalline residue will have its horizontal dimensions shortened. Third, there may be a warping of the walls of a sheet; the forces which are expected to compress part of the sheet to such a degree that other parts are thickened are not described. It would seem that there is no reason to assume a *central* accumulation of the liquid in this case, any more than in the case of a laccolith, where an *upper* layer is supposed to accumulate. Both sheets and laccoliths have competent roofs. Both are likely to have their upper layers solidified early.

There are thus outlined three cases in which Bowen finds no mechanical difficulty in imagining an action like a filter press. Two fundamental objections may be raised and should be answered before final acceptance of the idea. The first has to do with the structures left in the crystalline mesh after expulsion of the fluid; the second is a matter of the completeness of the separation, and the volumes of the separated parts.

Structures.—These three types of filter-press action occur when the mass is 80 per cent or more crystalline. Such a mass would have the crystals pretty well locked together. Uniform spheres closely packed take up only about 75 per cent of the space in which they are packed. Packed angular grains may occupy as little as 50 per cent. Even 5 per cent further growth would result in a fairly firm bond between adjacent crystals. If now the mesh

[1] Bowen carries the idea too far when he attempts to apply it to the Duluth lopolith. Lateral thrust on a sunken basin would hardly tend to dome up the roof. Furthermore he makes an inaccurate copy of a map published with a plain statement that the area on which he bases his argument had not been mapped in detail.

EDITORIAL NOTE: In this connection it may be said that the map which Dr. Bowen states that he copied is the map printed as Fig. 6 in the *Journal of Geology*, Vol. XXVI, p. 446. The map which Dr. Grout apparently has in mind in this connection is the map reproduced as Fig. 1, Vol. XXVI, of the same *Journal*, p. 628. The differences between the two are very slight.

was deformed, the crystals would be broken and bent in rather violent fashion. Rock flowage would be evident in the examination of the grains. It is possible, of course, that the temperature is so high and conditions so favorable for recrystallization that some of the strain effects would later disappear, but the broken crystals of porphyries and such rocks as the Sudbury norite argue against such effects. Even if recrystallization occurred, the process would be accomplished under stress and an orientation of grain would be almost inevitable. It is worth while, then, to investigate the cases of supposed filter-pressing for signs of structure and deformation. It would be a strong confirmation of Bowen's argument if a laccolith or sill could be cited in which the fluxion structure corresponded to the position of such differentiates as he describes. Neither Bowen, Judd, Barrow, nor Harker makes any mention of such an orientation. On the contrary, in the illustrations of the glass supposed to have oozed into vesicles Judd and Harker show exactly the opposite orientation. It looks much more as if a lump of solid glass had interfered with the haphazard position of the crystals.

Turning to the special case of Duluth, Bowen takes up a final suggestion of the mechanics of filter-press action by proposing a theory to account for the rocks described.[1] The great lopolith shows a sunken structure at present, and on that basis it may be assumed that there were some movements during crystallization.[2] Bowen believes that movements when the mass is 50–65 per cent crystalline would tend to produce bands and layers by the bridging action of the feebly interlocked crystal mesh. The reality of the bridging effect in a crystal mesh need not be questioned, but a more detailed report of the experimental work which led him to the suggestion and to the estimate of 50–65 per cent of crystals would be welcome. He has previously[3] stated an opinion that a magma with 50 per cent crystals was eruptible, and the bridging effect was ignored.

[1] *Jour. Geol.*, XXVII, p. 411.

[2] The main subsidence must have occurred before crystallization, for the mass is too thick to be supported isostatically as a dome. It is not improbable, however, that movements continued.

[3] *Jour. Geol.*, Supplement, November-December, 1915, p. 31.

The effect of the bridging tendency in such a crystallizing magma is stated in Bowen's words; the liquid must flow "into the space immediately below it, if the potential bridge is to become a reality." It is a most significant point that the motion is at right angles to the bands, each crystallizing layer contributing liquid to form a layer just below or just above. Furthermore, the deformation produced in the "weak yielding segment" is from lateral compression. Both the flow and the deformation would produce a *vertical* orientation. As a matter of fact the bands in the Duluth gabbro show many instances of orientation parallel to the bands and not one at right angles. It should be noted also that any filter-press action at Duluth must have stopped before much interlocking of crystals occurred, for there is very little sign of broken or bent crystals—three or four grains in hundreds of sections. There are enough to show that signs of strain may be preserved, but are so few that no general deformation is likely. Here, as in the previous cases that Bowen outlines, the evidence of structure is emphatically opposed to the action he suggests.

Completeness of separation and volumes of the separates.—If we assume, as seems probable, that liquid may be squeezed out from a crystal mesh 50–80 per cent crystalline, how complete a separation can be effected? In the banded portion of the Duluth gabbro the main rocks are olivine gabbro with only slight changes in proportion of minerals, but the bands of extreme composition are just as truly bands as the rest, and are evidently formed in the same way. Can an anorthosite be squeezed out of the same olivine gabbro as a peridotite? Or must we assume that the peridotite was the *residue* after the average gabbro liquid was squeezed out? If we assume that peridotite is a residue, can we assume for a neighboring band that anorthosite was the residue after the same average gabbro was squeezed out?

Bowen notes that the contrast between bands should be of a different order of magnitude from that shown in the gabbro-granophyr association, implying that the variation in the bands is relatively slight. The bands vary from rocks 98 per cent plagioclase to rocks 90 per cent magnetite, and include peridotites with no

feldspar and troctolites with no augite. The extremes are 100 per cent different, and are not to be expected from filter-pressing.

Taking next the case of granite separated from gabbro, we find it a general rule that the separation has proceeded to such a degree that the granophyr diabase is very small in bulk.[1] Such action develops only after the magma is 80 per cent crystals. The occurrence of 300 feet of red rock above gabbro with practically no granophyr, as described at Duluth, should mean that over 1,200 feet of gabbro was almost completely drained of all 20 per cent residual fluid—so completely that the trifling residue left no determinable mineral and produced no zoning of the feldspars. Such thorough drainage from so large a mass seems very unlikely. And if the 80 per cent crystal mesh had any strength at all it must have refused to yield so completely as to leave no interstitial magma at all. Interstitial granophyr would be much more likely to be trapped among crystals than as blebs in an immiscible liquid.

SUMMARY

In igneous magmas the movements which are subject to some disagreement are convection, crystal settling, and the expulsion of residual magma from a partly crystalline mass. An attempt is made to remove certain misconceptions of the convection process and its effects. The process of crystal settling seems to be limited to effects which may be estimated to extend not over 100 feet. Attention is called to several difficulties in the application of the filter-pressing idea. The writer favors all three of the ideas as working hypotheses, but certain critical field relations should be sought for before accepting either in specific cases.

[1] Frank F. Grout, "A Type of Igneous Differentiation," *Jour. Geol.*, XXVI (1918), pp. 645–57.

DEFORMATION OF CRYSTALLIZING MAGMA

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In the foregoing paper Professor Grout raises certain objections to processes that I have advocated as significant in petrogenesis, and to some of these objections I wish to take the opportunity, offered by the editors, of making a brief reply.

With particular reference to the Duluth gabbro, Grout says that "the arguments for circulation are conclusive," but offers no further support for the arguments than that formerly offered. The banding and fluxion structures are conclusive evidence of circulation of a sort, perhaps, but not necessarily of convective circulation. Convection suffers from the disability of requiring the further assumption of rhythmic crystallization, i.e., crystallization which is periodic with respect to the nature of the substance crystallizing. In this manner it is hoped to obtain alternating layers of different composition, but it would seem much more probable that convection would effect a thorough mixing of the successive products. The rhythmical crystallization itself is, moreover, an assumption that has nothing to support it in the whole realm of crystallization phenomena. The Liesegang ring effect is a totally different affair, and any assumption of rhythm in crystallization, such as Grout pictures, should be made only *in extremis*.

On the other hand the down-warping of the tabular mass of crystallizing magma would seem to necessitate the development of fracturing along planes sensibly parallel to the tabular extension of the mass. The crystalline mesh would be subject to an action that is to all intents and purposes thrust-faulting along these planes. This action opens the possibility of the filling of the fault "fissures" with liquid from the interstices of that portion of the adjacent mesh that happens to be weakest and of developing layers

that have approximately the degree of contrast shown between crystals and residual liquid at the time the action takes place. It must be understood, of course, that the crystal mesh is very weak and not capable of sustaining open fissures, but that local crushing of the mesh, formation of "fissures," and their filling with liquid are absolutely synchronous.

Such action, oft repeated as the warping continued, would seem to be thoroughly competent to produce the banded structure; nor does it fall behind in ability to produce fluxion structures. The flow of liquid through the pores of the adjacent mesh would not be particularly directional, but in its action of filling the "fissure" it would spread laterally and crystals would be correspondingly oriented. At first thought one might ask: "What crystals?" but it can scarcely be doubted that the thrusting action pictured would result in tearing a multitude of crystals from their relatively insecure moorings along the walls of the thrust planes and in their distribution by the liquid filling the "fissures."

Both the banding and fluxion seem, then, to be readily accounted for by the warping of the mesh as described, but the full consequences of such action are not yet exhausted. The liquid filling the lenticular openings developed carries, as we have seen, a certain amount of crystals, and the alignment of these marks the fluxion structure, particularly where the lenses are thin. In thicker lenses settling of these already large crystals will immediately take place when they are heavy, and there may develop from their accumulation the most extreme of monomineralic layers. Moreover, the liquid, thus purged of its suspended crystals, begins to crystallize itself under conditions that could scarcely be more favorable for differentiation by crystal settling. The temperature gradient is exceptionally low for a liquid mass just beginning to crystallize. Slow cooling and freedom from convection, the arch enemy of differentiation, are thus assured and the extent to which sorting of crystals is carried as these quiet pools crystallize is not likely to be matched in any ordinary type of intrusion. Not only the normal bands of moderate contrast may be produced by this warping action, therefore, but also bands of the most extreme types as an ultimate consequence.

We may pass on now to a consideration of the squeezing out of liquid at a still later stage of crystallization to form a distinct differentiate such as a granophyre mass. The breakdown of the crystal mesh at this stage would still, I believe, be accomplished by fracturing along areas of contact between two adjacent crystals and subsequent revolving of the crystals into a position permitting closer packing. There is later, too, a further growth of crystals dependent upon the amount of liquid ultimately left in the interstices, and the final result would be a panidiomorphic granular (not granulated) mass showing normal crystallization textures. The production of broken crystals and of granulation belongs to a later stage, when there is a negligible amount of interstitial liquid and shearing forces of a much greater order of magnitude must be brought into action. In all probability such forces do come into play in the production of some anorthosites, but far-reaching results can be produced by filter-press action without any necessity for the development of granulation.

In the case of production of a granophyric body from gabbro magma by expressing of liquid, there is no necessity that the gabbro should show granophyric interstices, for if the cooling is slow enough the granophyric liquid that remains in the interstices may be used up and normally will be used up by reaction with crystals already separated. No one who has examined a section of a gabbro with granophyric interstices can have failed to see the reaction referred to, interrupted before completion. The reaction between relatively large blebs of granophyre produced by immiscibility, while it might be of the same nature, could not possibly be carried to completion.

In conclusion I wish to confess some surprise at Grout's statement that I have made an inaccurate copy of his map of the Duluth gabbro, for the copy was made for me by a competent draftsman. Furthermore, my surprise has been greatly increased on examining my map, going over it minutely with a pair of dividers and finding that it corresponds absolutely, dimension for dimension, with Figure 6 of his paper, "Internal Structures of Igneous Rocks."[1]

[1] *Jour. Geol.*, XXVI (1918), 446.

Reviews

Geologic Map of Brazil. By J. C. Branner. Geological Society of America. "Outlines of the Geology of Brazil With Map." Vol. XXX, pp. 189–338. 1919.

Branner's Geologic Map of Brazil (Plate I) covers an area as large as that of the United States between the 49th parallel and Mexico, approximately three million square miles. It is on the scale of 1:5,000,000 or 1 inch to 80 miles. It is thus a wall map similar in scale and scope to the Geologic Map of North America of 1911.

This important contribution to our knowledge of South America centers chiefly in the geologic map, to which the accompanying text, although it comprises 150 pages, is merely an accessory. The base map was prepared by Dr. Branner, who constructed it in accordance with all available geodetic data and the personal information which he had gathered, supplemented by the maps listed in the accompanying text. The geologic coloring represents the distribution of the major stratigraphic divisions completely and in some detail for the eastern states, stands for reconnoissance in the Amazon region and along the foothills of the Andes, but is lacking over the central plateau for an area of approximately 500,000 square miles. There are also some other lacunae representing the imperfections of even general information regarding the geology. One of the most conspicuous, because it occurs in an otherwise well-known part of the country, traverses Minas Geraes and Bahia and covers the line of contact between Lower and Upper Permian, which cannot be traced with accuracy in this strip.

The geology is sketched very broadly. Thirteen divisions of the geologic column are represented, namely:

13 Quaternary	7 Upper Permian
12 Miocene and Pliocene	6 Lower Permian
11 Eocene	5 Carboniferous
10 Cretaceous	4 Devonian
9 Igneous rocks of Mesozoic age	3 Silurian
8 Triassic	2 Early Paleozoic
	1 Archean

It is obvious that there are large breaks in the sequence, due either to lack of knowledge or to unconformities. Both conditions exist. Geologic history is meagerly recorded in the great plateau of Brazil, which, in many respects, closely resembles the Laurentian Plateau of Canada and its marginal areas. Our knowledge of the record as far as it exists is also very incomplete.

The author says:

> In view of the limitations of our knowledge, it is not possible to represent on the map more than thirteen subdivisions of the geologic column. In some localities many more subdivisions are known and, over a limited area, might have been shown, but there would be no particular object in giving all of these subdivisions on a map of this scale. The minor details, even where they are known, are necessarily omitted on account of the small scale of the map. In regions of horizontal rocks, where partings are dendritic in form and outliers are abundant, these features cannot conveniently be shown. The areas of old crystalline schists are almost everywhere traversed by dikes of eruptive rock, but these dikes are usually too small to be shown on the map of the scale of this one. The same thing is true in the southern states, where numerous dikes cut all of the rocks below the Cretaceous.

The degree of generalization in classification in the map of Brazil is similar to that of McGee's geologic map of the United States (1884), but only a small portion of the map of Brazil is based on detailed topographic and geologic surveys like those which were available to McGee. Rather might we compare Branner's map with that of the United States by Marcou (1853)[1] or by Hitchcock and Blake (1874).[2] Dr. Branner himself has expressed the opinion that the geology of the United States was better known when Marcou published than is that of Brazil today. Branner's map is, however, far superior to Marcou's as a work in cartography, because of its rigid adherence to known facts, although it cannot be compared with Hitchcock's from the point of view of completeness of knowledge.

Judging by these criteria it is reasonable to state that knowledge of the geology of Brazil is more than half a century behind that of the United States. To a certain extent this may be attributed to physical difficulties, tropical vegetation, soil covering, and the general absence of fossils. But a more potent cause is the lack of general interest among

[1] Jules Marcou, "Résumé explicatif d'une carte géologique des Etats Unis et des provinces anglaises de l'Amerique du Nord, etc.," *Bull. de la Soc. Géol. de France Second Series*, Vol. XII, 1854–55.

[2] C. H. Hitchcock and W. P. Blake, Geologic Map of the U.S. in *Statistical Atlas*, Ninth Census, 1874.

the peoples of Brazil in geology, either from the scientific or the practical point of view. There are but few trained investigators in the country, and there is great need of adequate public sentiment to support either state or national surveys. Those far-sighted Brazilians who appreciate the importance of a knowledge of the geologic history and resources of their country advance but slowly against the lack of interest of the people and the inertia of the bureaucracy.

The scientific world will share with the author of this map the hope that his contribution to the world's knowledge of Brazil may stimulate interest among the people of that country in a truly scientific, thorough survey of their great domain. Many of the enlightened nations of the world are carrying on such a survey and regard its cost as a necessary charge on the national budget, because in the long run the advantage to the nation far more than outweighs the expense. It is, however, a mistake to assume that returns from the money invested in a geological survey are either evident or immediate. The principal object is to make and publish maps and reports which shall furnish reliable information regarding the country, and thus promote its development, increase its population, and augment its sources of revenue. Brazil greatly needs a well-organized topographic and geologic survey, such as can be executed only by a trained staff, in order to inform her own people and the world regarding her resources in agriculture, water powers, and mineral wealth, and also to promote the investment of capital on the sound basis of scientific knowledge.

The text accompanying the map includes an extensive bibliography of the sources of information which the author has discovered during what we may well call an exhaustive study of the subject. The list consists almost exclusively of the names of European and North American travelers and geologists. One of the earliest is von Eschwege, who occupied an official position in Brazil and wrote on the geology of the country just a century ago. Hartt, as head of the Geological Survey in the seventies, organized important investigations and himself made contributions to our knowledge, but he was rather a zoölogist than a geologist. His successor, Derby, who held the position as head of the Geological Survey up to the time of his death in 1915, stands officially for the principal work carried out under national auspices. With these should be named Dr. Gonzaga de Campos, a Brazilian geologist who has done much to advance the exploration of his country and is still in active service. There are many distinguished names in the list of investigators cited by Branner, but there is none who has brought to the

study an equal understanding of stratigraphic and structural problems or has pursued the investigation so persistently as has Dr. Branner himself.

In his foreword the author states:

> The accumulation of the data for the geologic map of Brazil was begun by me in 1874, when I first went to that country, and has been kept up as opportunities offered, down to the present time. The gathering and study of the material and the preparation of the map may therefore be said to represent the work of a considerable portion of a lifetime.

In addition to the large amount of information secured through his own personal observation the author has utilized the work of his several assistants, who have accompanied him on his expeditions to Brazil, and he has availed himself of every scrap of published or unpublished data which could stand the rigid scrutiny to which he subjected it. His resources in every direction have been unusual, but what stamps the map with authority is the character of its author, whose life-work in Brazil it epitomizes.

The geologic facts recorded in the map and accompanying text will serve three classes of students. Those who are interested in the history of Brazil as an example of the geological development of a great continental nucleus will find in the summary comprised under "Outlines of Stratigraphic Geology," pp. 202–23, a brief but comprehensive statement. Those students who may be interested in the geology of individual states or in local details will turn to the general geology described by states in alphabetical order, and to the bibliography which follows the statement regarding each state; and those who are chiefly interested in the economic resources will find valuable notes also under the separate articles regarding individual states.

Branner's text is in itself a summary. As may be seen by reference to the extensive bibliographies accompanying the descriptions of the several states, a full discussion would constitute a large volume. In order, however, to indicate the general facts of the geology in bare outline the summary may be summarized as follows:

The Brazilian complex, or basement, of the Brazilian plateau of South America is a mass of crystalline metamorphic and eruptive rocks, granites, gneisses, and schists, which closely resembles the Archean complex of the Canadian shield. They constitute the surface in the eastern mountain ranges and plateaus, forming a broad belt all along the Atlantic Coast, except in the far south. They occur both north and south of the geosyncline of the Amazon Valley, and outcrop at numerous

points in the plateau of Matto Grosso. Occurring either in these rocks or derived from them are gold, copper, platinum, tungsten, mica, marble, talc, apatite, graphite, potash-bearing rocks, precious stones, and building stones.

Distinctly younger than the Brazilian complex or Archean is a sequence of metamorphic rocks of unquestionable sedimentary origin, consisting of quartzites, schists, limestone, and the great iron-bearing formations of Minas Geraes. These strata occur imbedded in the Archean, which unconformably underlies them and by which they are in part covered in consequence of overthrusting. Their age is indeterminate, as no traces of fossils have been found, but they are assigned by Branner to the early Paleozoic.

It is evident that a period of profound diastrophism intervened between the deposition of these "early Paleozoic sediments" and the next succeeding strata, which are sandstones of Silurian (Niagara) age. To the systematic geologist it is a question of some importance whether the deformation occurred in the early Paleozoic or possibly in pre-Paleozoic time, as might be the case if the metamorphosed sediments belonged to the pre-Cambrian. It would seem that we have here a problem not unlike that of the later pre-Cambrian formations of the Lake Superior region which, by some geologists, are considered to include Cambrian rocks.

These ancient metamorphosed strata are economically of very great importance. They include the enormous iron deposits and the important occurrences of manganese. Gold-bearing veins occur in them, and the diamonds and other precious stones of Brazil are supposed to have been derived from them.

The Silurian sandstones already referred to are the oldest fossiliferous rocks known in Brazil. They are of Niagaran age and occur on the northern side of the Amazonian geosyncline, dipping gently southward. Branner expresses the opinion that it is highly probable that there are rocks of Silurian age in other parts of Brazil, but none have as yet been identified by fossils.

Strata of Devonian age occur at widely separated points in Brazil. They are found north of the Amazon, in São Paulo and Paraná in the south, and in Matto Grosso in the west. They consist of white and yellowish sandstone and black and reddish shales. In the Amazon region, although they dip at a very low angle and are not otherwise disturbed, they are cut by dikes of diabase. In Paraná and southern São Paulo the Devonian rocks seem to rest directly on the Brazilian

complex and dip gently westward beneath the Permian. They consist of conglomerates, sandstones, and shales, and the conglomerates of Paraná are supposed to be the source of the diamonds of that state.

Upper Carboniferous beds, containing marine fossils, are exposed in the state of Pará and also in Amazonas, north of the Amazon River. They are shales, sandstones, and limestones, aggregating about 600 meters in thickness, but they contain no coal. In Bahia certain quartzites, sandstones, and conglomerates which yield diamonds and carbonados are doubtfully assigned to the Carboniferous. Branner discusses in some detail the relation between these diamond-bearing strata of Bahia and the diamond-bearing quartzites of Minas, and inclines to the opinion that they are stratigraphically equivalent. The Carboniferous rocks are not now known to contain other resources of economic significance.

The pre-Permian Paleozoic strata, which have been briefly described, appear to be restricted to somewhat local occurrences and to represent a moderate degree of sedimentation. It would seem as though Paleozoic history in Brazil had been characterized by very gentle movements of uplift and depression and correspondingly scanty erosion. The Permian, on the contrary, is composed of two widespread series Lower and Upper Permian, each of very considerable thickness. A belt of Permian rocks from 100 to 500 miles wide, more or less, extends from near the Atlantic Coast east of the Amazon, southward continuously through all the intervening states, to Santa Catharina, a distance of 2,000 miles. East of it lies an even broader belt and one of equal length, consisting of the Brazilian complex and the infolded Paleozoic rocks. The latter constitutes the Atlantic Coast ranges of Brazil and the eastern part of the Brazilian plateau, while the Permian rocks form the surface of the plateau farther west. The Permian rocks were apparently deposited in a great geosyncline, which developed in the strip where they now occur along the western base of a mountain range that furnished the materials for the sandstones and shales. There is thus evidence that eastern Brazil was mountainous in Permian time as it is today, and there is a certain parallelism between the orogenic structure of eastern South America and that of the eastern United States in Permian time.

Branner summarizes the description of the Permian of Brazil, saying that the rocks "seem to be mostly sandstones and shales, slightly disturbed, but they include extensive beds of limestone—all of them cut here and there by eruptive dikes. In São Paulo, Paraná, and Santa Catharina the Lower Permian contains glacial till with striated boulders."

He discusses at some length the evidences of the age and extent of the Permian glaciation, and cites the observations of a number of geologists and travelers upon the occurrence of the strata and fossils by which they have been identified. He distinguishes the Upper and Lower Permian, both in his text and on the map, except that he has not indicated the boundary between the two where its location is not definitely known, on the headwaters of the Rio São Francisco. The Upper Permian is described as unconformable upon the Lower, but the break is marked only by a change in sedimentation.

The coal beds of Paraná, Santa Catharina, and Rio Grande do Sul are economically important, as are also the Permian bituminous shales of the southern states. The limestones will yield materials for the manufacture of Portland cement.

The pre-Mesozoic rocks, including the Permian, constitute the mountains and plateaus of all of eastern Brazil, which is thus a great geologic province whose history since the close of the Paleozoic has been that of a continental area subject to erosion. With the exception of small areas of Tertiary rocks along the Atlantic Coast and an embayment of Cretaceous and Tertiary strata in Bahia and Piauhy there are no post-Paleozoic sediments in the area.

The Mesozoic rocks occur southwest and west of the great Brazilian plateau. They comprise the red sandstones of the Trias, extensive outflows of pre-Cretaceous igneous rocks, and sandstones and limestones of Cretaceous age. The Trias is most widely represented in western São Paulo and southern Goyas. The igneous rocks, erupted through the Trias and spreading out as very extensive lava flows similar to those of the Columbia lavas, occur in Rio Grande do Sul, Santa Catharina, Paraná, and São Paulo. They occur as interbedded sheets exposed along the canyon of the Paraná, where, on account of the small scale, the coloring of the map gives an appearance of a widespread igneous mass under the Trias.

The Cretaceous is distributed in the form of remnants capping the Triassic plateaus, and extends northwest across Matto Grosso to the Andes and also north to the Amazon Valley. In the northwest and north it appears to rest directly upon the Brazilian complex, the older rocks being absent.

The Tertiary formations of Brazil are briefly described as comprising freshwater and land deposits of the territory of Acre, brackish water deposits in Amazonas, and marine deposits in Pará, Maranhão, and also in Rio Grande do Norte. Marine Tertiary occurs along various sections

of the coast, and Tertiary lake beds are found in Rio de Janeiro, São Paulo, and Minas.

Following the systematic summary of the geologic series represented in Brazil, Branner gives a fuller account of the geology of each province, and with it a bibliography of the works of travel and scientific exploration describing that state. The outline concludes with statements regarding the economic resources and mining laws of Brazil.

It was not the author's purpose to give a full discussion of the geology of Brazil. He refers, on the contrary, constantly to the original documents upon which he has drawn to supplement his own personal knowledge.

Dr. Branner has, with the aid of the Geological Society of America, made a very important and fundamental contribution to the geology of South America. The Society is to be congratulated upon the service it has thus rendered to science. The author also is to be felicitated, but he has the deeper satisfaction of having achieved the purpose of a lifetime, of having laid the foundations of the geology of Brazil firmly in an exact account of the present state of knowledge.

Note.—The *Outlines of the Geology of Brazil* with the geologic map is published in the usual edition for the use of the Society, in English, and in a Portuguese edition of 1,000 additional copies. There are also 500 extra copies of the map. It is regrettable that the number of copies of the text and map available to the general public is so limited.

In many paragraphs the reader will be embarrassed by the lack of any means of identifying the localities named. It was not possible to put all the names or any large part of them on the map. Neither do they all occur on maps contained in the usually available atlases. An index of place names, giving the location by latitude and longitude, would have been of great assistance.

Translations of the quotations which are given in the original languages, notably of the Portuguese, would have helped many readers.

Bailey Willis

EXPLANATION OF PLATE XII

The accompanying map is a reduced photograph of the original and, in order to make it legible, numbers have been inserted on the principal areas of the different formations. The following is the list of formations distinguished:

13. *Quaternary.*—Alluvial deposits, stone reefs of the northeast coast, and the sandstones of Fernando de Noronha.


MAPPA GEOLOGICO
DO
BRAZIL
COMPILAÇÃO DE
JOHN CASPER BRANNER
1918
VENEZUELA
COLUMBIA
GUYANA INGLEZA
GUYANA
GUYANA FRANCEZA
PERU
BOLIVIA
ARGENTINA
MINAS
RIO GRANDE
LEGEND

12. *Miocene or Pliocene.*—Tertiary of the upper Amazon, the coast and lake beds of Minas, São Paulo, Bahia, and Rio de Janeiro. Catinga limestones, Bahia.

11. *Eocene.*—Maria Farinha, Olinda, Pernambuco, Alagoas, Piabas, Maranhão, Natal, and the coast.

10. *Cretaceous.*—Sergipe, Bahia, Serra do Araripe, Ceará, Parahyba. Parecis beds of Matto Grosso. Baurú of São Paulo (Wealden) Marahú Bahia. São Bento series of Santa Catharina.

9. *Igneous Rocks.*—Pre-Cretaceous igneous, alkaline rocks and their associates, including nephelene syenite, foyaite, tinguaite, phonolite, syenite, trachyte, gabbro, diabase, diabase-basalt, and the Triassic "trap" of the southern states.

8. *Triassic.*—Maracajú of southern Matto Grosso; Botucatú of São Paulo; Rio do Rasto of Santa Catharina; Santa Maria, Rio Grande do Sul with Scaphonyx.

7. *Upper Permian.*—Passa Dois series of Santa Catharina, Stereosternum and Mesosaurus beds with cherty concretions of São Paulo. Piauhy, Bahia (Aricy); Estancia beds of Sergipe, Maranhão e Goyaz (Psaronius beds), Matto Grosso.

6. *Lower Permian.*—Tubarao series of Santa Catharina; coal beds of southern states with Glossopteris flora; glacial beds, Orleans conglomerate. Serra Grande series of Piauhy and Ceará of Small. Salita Limestones, Bahia Limestones of Rio das Velhas.

5. *Carboniferous.*—Marine beds of Rio Uatuma, Frechal e Pedra do Barco in Amazonas; Itaituba, Trombetas, Maecurú and Curuá, Para; Lavras quartzites of Bahia.

4. *Devonian.*—Ereré (above), Maecurú and Curuá in Amazon valley. Ponta Grossa shales in Paraná; Chapada in Matto Grosso; Caboclo shales, Bahia.

3. *Silurian.*—Rio Trombetas, state of Pará. Tombador in Bahia Cuyabá slates, etc.

2. *Early Paleozoic.*—Itacolumite? Iron manganese and schists of Minas Geraes; quartzites of Serra de Jacobina and elsewhere in Bahia. Lisboa's Bodoquena of Matto Grosso.

1. *Archean.*—Brazilian complex: gneiss, schists, granite.

Quicksilver in 1918. By F. L. RANSOME. Mineral Resources of the United States, 1880. U.S. Geological Survey.

There were no events of conspicuous importance or unusual interest in the quicksilver industry in 1918, but Dr. Ransome's annual review of the industry for that year is noteworthy not only as an excellent concise review of the industry, but because it contains a twelve-page list

of all of the quicksilver mines of the United States, giving their location, name and address of owner, general character of the deposit, nature and extent of the workings, reduction equipment, and estimated production to the end of 1918.

The report closes with a list of recent publications on quicksilver in the United States, Canada, and Mexico.

E. S. B.

Peat in 1918. By C. C. Osbon. Mineral Resources of the United States, 1918. U.S. Geological Survey.

The peat industry, though still one of our smallest mineral industries, exhibited somewhat surprising growth in 1917 and 1918, attaining in the latter year a production record about three times that for any year prior to 1917. This growth has been due partly to an increase in its use for fuel, especially in New England, but also to the development of other uses, such, for example, as its incorporation in commercial fertilizers and its use in the preparation of stock foods, partly as an absorbent for other components, but also because of its nitrogen content, which averages about 2 per cent. During the war over half a million absorbent surgical dressings were made in this country from peat moss and sent to our armies. The report constitutes an excellent brief review of the origin and distribution of peat in the United States and includes a map, 18×28 inches, showing in colors the distribution of our peat deposits and the location of peat-producing plants.

E. S. B.

Recent Publications

—Jones, E. L., Jr. A Reconnaissance of the Pine Creek District, Idaho. (Contributions to Economic Geology, 1919, Part I, pp. 1–36.) [U.S. Geological Survey, Bulletin 710-A. Washington, 1919.]

—Knopf, A. A Geologic Reconnaissance of the Inyo Range and the Eastern Slope of the Southern Sierra Nevada, California. With a section on The Stratigraphy of the Inyo Range, by Edwin Kirk. [U.S. Geological Survey, Professional Paper 110. Washington, 1918.]

———. Tin in 1917. [U.S. Geological Survey, Mineral Resources of the United States, 1917. Part I:7. Washington, 1918.]

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—Kreisinger, H., Augustine, C. E., and Harpster, W. C. Combustion Experiments with North Dakota Lignite. [U.S. Bureau of Mines, Technical Paper 207. Washington, 1919.]

—Latimer, W. J. Soil Survey of Barbour and Upshur Counties, West Virginia. [U.S. Bureau of Soils. Advance Sheets—Field Operations of the Bureau of Soils, 1917. Washington, 1919.]

—La Touche, T. H. D. (Compiler). A Bibliography of Indian Geology and Physical Geography, with an Annotated Index of Minerals of Economic Value. [Geological Survey of India. Calcutta: 27 Chowringhee Road. London: Messrs. Kegan Paul, Trench, Trübner & Co. 1918.]

—Leffingwell, E. de K. The Canning River Region, Northern Alaska. [U.S. Geological Survey, Professional Paper 109. Washington, 1919.]

—Lesher, C. E. Coal in 1917. Part A. Production. [U.S. Geological Survey, Mineral Resources of the United States, 1917. Part II:32. Washington, 1919.]

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—Lindgren, W. Mineral Deposits. Second Edition. [New York. McGraw-Hill Book Co., Inc., 239 W. 39th St., 1919. Price, $5.00.]

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—LOUGHLIN, G. F., AND COONS, A. T. Stone in 1917. [U.S. Geological Survey, Mineral Resources of the United States, 1917. Part II:30. Washington, 1919.]

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Diastrophism and the Formative Processes. XII. The Physical States of the Planetary Nuclei during their Formative Stages. XIII. The Planetesimals and their Infall. By T. C. Chamberlin.

Factors Producing Columnar Structure in Lavas and Its Occurrence Near Melbourne, Australia. By Albert V. G. James.

Pleistocene Mollusca from Indiana and Ohio. By Frank Collins Baker.

The Heart Mountain Overthrust. By D. F. Hewett.

Recent Studies of the Upper Cretaceous of Tennessee. By Bruce Wade.

Concerning the Process of Thrust Faulting. By Terence T. Quirke.

Notes on the Mechanics of Geologic Structures. By Warren J. Mead.

Geologic Reconnaissance of the Southern Part of the Taos Range, New Mexico. By John W. Gruner.

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THE CHESTER SERIES IN ILLINOIS[1]

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PART I

The Mississippian rocks in Illinois occupy three distinct areas along the western and southern borders of the state. The northernmost of these areas is the larger, and extends from southern Mercer County on the north to northern Madison County on the south. Throughout this entire distance, except for an interval in Pike, Calhoun, and Jersey counties, where older rocks are exposed, the rock formations of the Mississippian system constitute the Mississippi River bluffs. This area also includes the Mississippian strata which are exposed in the valley of the Illinois River as far north as Scott, Brown, and Schuyler counties. Nowhere in this area do the higher formations of the system occur, the youngest formation exposed being the Ste. Genevieve limestone, in the summit of the bluffs above Alton.

The second of the three areas occupies portions of St. Clair, Monroe, Randolph, and Jackson counties. This area includes about 85 miles of the Mississippi River bluffs from a short distance below East St. Louis to the gap formed by the valley of the Big Muddy River, and at only one locality in this entire distance, at

[1] Published by permission of the Directors of the Geological Surveys of Illinois and Missouri.

Valmeyer in Monroe County, are any formations other than the Mississippian exposed. The greatest width of this area is in Monroe County, where the Mississippian formations form the surface rocks for a distance of about fifteen miles back from the river bluffs, where they pass beneath the Pennsylvanian strata. Within this area both the lower and upper series of Mississippian formations are present, and it includes the typical area of the Chester series, as these rocks were described by Hall and Worthen more than half a century ago.

The third area of Mississippian rocks in Illinois is in the extreme southern portion of the state, where these formations constitute the surface rocks throughout a belt ranging from fifteen to thirty or more miles in width, across Union, Johnson, Pope, and Hardin counties. The greater portion of this area is occupied by the upper Mississippian formations of Chester age, although the lower formations do occupy considerable areas in Union and Hardin counties. The northwestern corner of this southern belt is separated from the central area by the valley of the Big Muddy River in Jackson County.

The main portion of this paper will be devoted to a discussion of the Upper Mississippian or Chester series, although the Lower Mississippian, or Iowa series as it may be called for want of any comprehensive name already in use, will be given some consideration in the discussion of the geological history.

The Iowa series was subdivided into a number of well-recognized formations more than half a century ago, mainly through the work of James Hall[1] in Iowa, although some attempt at subdivision had been made before Hall's time, and the subdivisions and classification has been somewhat elaborated in later years. In the main, however, the divisions established by Hall constitute the formations that are recognized at this time. Not so with the upper Mississippian. The early workers generally recognized in this series a more or less confused succession of limestones, shales, and sandstones, and but little attempt was made to subdivide the series. Hall gave the name Kaskaskia limestone to the whole of the succession above a conspicuous sandstone formation in the Mississippi

[1] *Report on the Geological Survey of Iowa* (1858).

River bluffs of Randolph County which was commonly called the "Ferruginous Sandstone." Worthen used the name Chester limestone for the same beds which Hall called Kaskaskia, but included this Chester limestone with the underlying sandstone in what he called the "Chester Group."

While both Hall and Worthen based their descriptions of the upper Mississippian rocks upon observations made for the most part in the second of the areas which have been mentioned, Henry Engelmann carried on field studies in the more southern counties of the state, under the direction of the Illinois Geological Survey. In Johnson, and in the counties to the east and west, Engelmann recognized an alternating succession of limestone and sandstone members of the Chester Group, ten in all, which he designated by the numbers 1 to 10, beginning the numbering at the top. The sandstones in the series received the even numbers and the limestone and shale members the odd numbers. The only one of these members to which a distinct name was given was No. 8, which was called the Cypress sandstone[1] from the good exposures in the bluffs of Cypress Creek, but even this name was abandoned in the later reports by Engelmann and was never used by Worthen.

The real importance of the Chester series in the Mississippian as a whole is well shown by its comparative thickness. The whole of the lower Mississippian or Iowa series has a thickness of approximately 1,000 feet, which was subdivided at an early time, as has been stated, into a succession of well-defined formations, but the Chester series, with a maximum thickness of more than 1,200 feet, commonly has been treated as a single formation by all geologists up to a very recent date.

The first serious attempt to subdivide the Chester was made by Ulrich[2] in 1905. He recognized four formations as follows: 4. Birdsville formation; 3. Tribune limestone; 2. Cypress sandstone; 1. Ste. Genevieve limestone.

The observations which led to this division of the Chester into definite formations were inadequate for the proper understanding of the whole series, and mistakes of so serious a character were

[1] *Trans. St. Louis Acad. Sci.*, Vol. II, Part 1 (1863), p. 189.

[2] Prof. Paper, *U.S. Geol. Survey*, No. 36.

made that it has not been possible to adapt any part of the scheme to the more recent work on the series. In the first place the Ste. Genevieve limestone was mistakenly included in the Chester Group because of the failure to recognize that the upper member of this limestone as defined, the Ohara, was really made up of two very distinct parts, only the upper one of which is really Chester, and this "Upper Ohara" really has no place whatsoever in the Ste. Genevieve limestone when that formation is properly limited in accordance with its typical exposures in Ste. Genevieve County, Missouri. In the second place the sandstone designated as Cypress by Ulrich was not the Cypress of Engelmann, but the bed that was properly sandstone No. 10 of that author. In the third place, beds which really belong in three totally different positions in the Chester series were designated as Tribune limestone. The limestone at Tribune, Kentucky, which gave origin to the name, has more recently been shown to occupy a position far above that designated for the formation, and is in fact representative of a limestone member far up in the Birdsville formation as defined by Ulrich. At another locality the so-called Tribune is a limestone beneath the sandstone that was mistakenly called Cypress, while elsewhere it does occupy the position assigned to it in the definition of the formation, above the miscalled Cypress sandstone. In the fourth place the Birdsville formation of Ulrich comprises a succession of limestones, sandstones, and shales, and is as lacking in utility as a formation as was the older name, Chester formation.

The work upon which the present paper has been based has been carried on continuously under the auspices of the Illinois State Geological Survey, from 1911 to the present time, and was preceded by more general observations upon the Chester series since 1906. From 1911 to the present time the work of mapping in detail the Chester series in Illinois has been in progress, and it has now covered the counties of St. Clair, Monroe, Randolph, Jackson, Johnson, Pope, and Hardin. The only portion of the Chester belt across the state that has not been studied and mapped in detail at the present time is in Union County and a corner of Jackson, and reconnaissance observations in Union County have

shown that very little if anything new in the section can be looked for there.

In the course of these studies it has been found to be necessary and perfectly practicable to subdivide the Chester series into sixteen distinct formational units, which can be distinguished and mapped with ease. The limestones of the series, with one possible exception, are all continuous across the state, from their first appearance from beneath the Pennsylvanian strata in St. Clair, Monroe, or Randolph counties, on the northwest, to Hardin County at the extreme southeastern part of the belt. The sandstone formations, however, are not all continuous across the state; one has its greatest development in the west, thins out, and disappears to the east. Several of them have their great development in the east and become much thinner or disappear entirely in the more western portion of the state. The two uppermost sandstones of the series, however, are present uniformly across the state.

This entire series of Chester formations in Illinois may be arranged in three larger groups that possess rather distinct faunal characteristics, and these three divisions may be designated as lower, middle, and upper Chester. The names of these Chester formations, with their arrangement in the larger divisions are as follows:

Upper Chester Group:

16. Kinkaid limestone
15. Degonia sandstone
14. Clore limestone
13. Palestine sandstone
12. Menard limestone
11. Waltersburg sandstone
10. Vienna limestone
9. Tar Springs sandstone

Middle Chester, or Okaw Group:

8. Glen Dean limestone
7. Hardinsburg sandstone
6. Golconda limestone
5. Cypress sandstone

Lower Chester Group:

4. Paint Creek limestone
3. Yankeetown formation, and Bethel sandstone
2. Renault limestone
1. Aux Vases sandstone

In the naming of these units, those formations are designated as limestones which include notable limestone beds. In all cases such formations include a considerable amount of shale, in some

cases, locally at least, more shale than limestone, and some of them do include minor arenaceous layers. They are called limestones, however, because they are primarily calcareous as distinguished from the alternating sandstone formations. Each of these formations will be considered briefly, their leading lithologic and faunal characteristics will be pointed out, as well as their geographic distribution in the state, and in some cases their distribution beyond the limits of Illinois, in part at least. This will be followed by some statements concerning the geological history of the Illinois basin in Chester time, and its relations to the history of the preceding Iowa time.

LOWER CHESTER GROUP

Aux Vases sandstone.—The Aux Vases sandstone is typically exposed in the Mississippi River bluffs of Randolph County, Illinois, and Ste. Genevieve County, Missouri. It is the formation that was called "Ferruginous sandstone" by the early Mississippi valley geologists, the name Aux Vases being first used by Keyes in 1892,[1] from the exposures in Ste. Genevieve County, Missouri, near the mouth of River Aux Vases. It was the belief of Engelmann and also of Worthen that this basal sandstone in the Mississippi River section was the exact equivalent of sandstone No. 8, or Cypress sandstone of Engelmann's Johnson County section. With such a correlation accepted, Keyes name would be synonymous with the earlier Cypress. In the assumption that the Aux Vases–Cypress correlation was correct, the name Aux Vases was abandoned in our earlier work in Illinois. It was early recognized, however, that there was a stratigraphic break within the arenaceous beds of the basal portion of the Chester series in Monroe and Randolph counties, and with the belief that the name Cypress covered all of these beds and that the Aux Vases was the exact equivalent of the Cypress, the name Brewerville[2] was used by the writer for that portion of the sandstone which lies beneath the break. Later, when studies in the more southern counties of Illinois established the fact that the Cypress and the old "Ferruginous sandstone" were not equivalent, and when studies

[1] *Bull. Geol. Soc. Amer.*, Vol. III, p. 296.

[2] *Trans. Ill. Acad. Sci.*, Vol. VI (1913), p. 121.

across the Mississippi River, in Missouri, showed that the typical section of the Aux Vases was the exact equivalent of the beds for which the name Brewerville had been used, the latter name was abandoned and the name Aux Vases adopted for the lowest sandstone formation of the Chester series in the Mississippi River section.

In its surface outcrop this formation is restricted to a belt through Monroe and Randolph counties, Illinois, continuing into Ste. Genevieve County, Missouri. The formation is a very massive, fine- or medium-textured sandstone in thick beds, in most places more or less conspicuously cross-bedded. Its color on freshly broken surfaces is a soft brown tint, in some localities becoming nearly white. Not infrequently it is mottled with small, dark-brown specks. On long-exposed weathered surfaces, the color in most localities is a darker brown than that of freshly broken surfaces. The massiveness of the formation is well shown in the Mississippi River bluffs between Prairie du Rocher and Modoc and in some of the picturesque gorges which have been eroded in the formation where it is crossed by stream valleys. No fossils of any sort have been found in the Aux Vases sandstone in Monroe or Randolph counties.

The unconformable relations of the Aux Vases sandstone upon the underlying Ste. Genevieve limestone are well shown in a number of places in Illinois. The uneven line separating the two formations can be clearly seen in the Mississippi River bluffs above Modoc. Elsewhere there is an important basal conglomerate in the Aux Vases, such conglomerates being well exposed two miles southeast of New Design, in S.E. $\frac{1}{4}$, S.W. $\frac{1}{4}$, Sec. 28, T. 3 S., R. 9 W., and again five miles southeast of Waterloo in the bluffs of Rock House Creek, in S.W. $\frac{1}{4}$, Sec. 4, T. 3 S., R. 9 W. Still another excellent exposure of the basal conglomerate, apparently resting upon the St. Louis limestone rather than the Ste. Genevieve, is about 6 miles west of Red Bud, in S.E. $\frac{1}{4}$, N.E. $\frac{1}{4}$, Sec. 4, T. 4 S., R. 9 W. A very excellent exposure of this same basal conglomerate is exposed in the Mississippi River bluffs just below McBride, Perry County, Missouri. The pebbles in these conglomerates are practically all chert, they are more or less angular for the most part,

and were clearly derived from the underlying Ste. Genevieve or St. Louis limestones.

The presence of these conglomerate beds establishes the fact that subsequent to the deposition of the Ste. Genevieve limestone, the calcareous sediments hardened into limestones, the cherts which are clearly secondary in origin were formed, and were in essentially the same condition in which they are found today. Then an erosion period set in and in places the entire thickness of the Ste. Genevieve limestone was removed, along with a part of the St. Louis limestone. The subsequent sedimentation laid down the sands of the Aux Vases formation. This interruption in the deposition of the sediments of the Mississippi Valley section must have represented a considerable length of time, and it must be reckoned as an important break in Mississippian history. Other phenomena connected with this sedimentary break will be discussed later, in connection with the geological history.

Beyond Monroe and Randolph counties, to the south, the Aux Vases sandstone has not been certainly identified. There is, however, a flaggy sandstone, about 20 feet thick, in the base of the Chester section east of Anna, in Union County, Illinois, which may be an extension of the Aux Vases, but in view of the fact that this sandstone contains numerous fossils in some beds, while the Aux Vases is quite barren of fossils, and further that sandstone beds are commonly present in the Renault formation of Monroe and Randolph counties, it is possible that this Union county sandstone may be younger than any part of the Aux Vases, and is perhaps referable to the Renault.

The maximum thickness of the Aux Vases sandstone is about 75 or 80 feet, and it varies from this amount to nothing at all, for in places the overlying Renault formation overlaps the Aux Vases and rests upon the underlying Ste. Genevieve limestone. In the more southern counties of Illinois, east from Union County, the position of the Aux Vases sandstone in the section is represented by an unconformity in the midst of the so-called "Ohara limestone member" of the Ste. Genevieve limestone, as described by Ulrich.

Renault limestone.—It would perhaps be better to call this unit the Renault formation, for in addition to its limestone content it

includes much shale and sandstone. It is, however, the first epoch of calcareous sedimentation in Chester time, and while locally there were considerable accumulations of clastic materials near the shore lines of the period, at a distance from the shore the material deposited was wholly limestone and calcareous shale. The name of the formation has been derived from Renault township, the southernmost township in Monroe County. The belt of outcrop of the formation crosses the whole of Monroe County in a north and south direction, and extends northward across the southwestern portion of St. Clair County and southward across the northwestern corner of Randolph County. The outcrops of this formation along Hickman Creek, in St. Clair County, are the most northerly exposures of any Chester formation. In a southerly direction the formation is exposed west of the Mississippi River across the southeastern corner of Ste. Genevieve County, Missouri, and continues for a short distance into Perry County.

Throughout the area of outcrop of the Renault in these Mississippi River counties, the formation is constituted of a very great variety of sediments, limestone, sandstone, and shale being represented, with each type of rock exhibiting great variation in its lithologic characters. In fact, one of the characteristics of the formation in this typical region, is its notable heterogeneity. This great variety in sedimentation is doubtless due to the beds having been laid down in proximity to the shore line of that time.

Beyond the Mississippi River counties, the Renault is known in Union County and from here it outcrops in a continuous belt, except where it is interrupted by faulting, across Illinois to Hardin County, and is also known across the Ohio River in Kentucky. In Union County the formation contains a considerable amount of clastic material in its lower part, perhaps including the flaggy sandstone east of Anna, which has already been mentioned as possibly representing the Aux Vases. Besides this sandstone and some overlying, variegated shales there is nearly or quite 100 feet of limestone referable to the Renault in the Union County section, and the limestone continues across the state, but not everywhere with this thickness. In the southeastern part of the state, especially in Hardin County, and also in Crittenden County, Kentucky,

there are some shaly beds at the base of or just beneath the Renault which have been called the Shetlerville formation, from Shetlerville, Hardin County, Illinois. These beds might perhaps be considered as a member of the Renault rather than as a distinct formation, but they are characterized by certain faunal elements that are somewhat different from the overlying Renault. There is some reason to believe that the Shetlerville beds are represented in the lower portion of what has been called Renault in Union County, but further detailed field work is necessary to establish such a conclusion. East of Union County all of the beds of the Renault or Renault-Shetlerville interval are limestones and more or less calcareous shales.

In the region of its typical development in Monroe County, Illinois, the Renault exhibits a maximum thickness of about 100 feet, but it varies from this maximum to a minimum of less than 20 feet, and doubtless actually thins out to nothing at all. The exposures of the formation in Ste. Genevieve County, Missouri, vary in thickness from about 46 feet to 75 feet or more, and there may be a maximum thickness of 100 feet in the county. In Union County there is 100 feet or more of Renault, but to the east of this county the formation in combination with the Shetlerville, is somewhat less than this, varying from 60 to 80 feet in most sections.

The Renault formation rests unconformably upon whatever lies beneath it, wherever it has been observed in Illinois and Missouri. In the Mississippi Valley counties it overlaps the Aux Vases sandstone and in many places rests upon the older Ste. Genevieve or even on the St. Louis limestone in places. The sub-Renault unconformity is well indicated by the presence of a basal conglomerate at a number of widely separated localities. The best exhibitions of this conglomerate are in St. Clair County, Illinois, on a tributary of Hickman Creek three miles northwest of Millstadt, and in Ste. Genevieve County, Missouri, about halfway between the mouth of Saline Creek and St. Marys. In both of these localities the underlying formation is the Aux Vases sandstone. The conglomerate is constituted of rounded pebbles of chert with an occasional pebble of igneous rock, ranging in size from two inches in diameter to a fraction of an inch. All through the southern counties of Illinois

the Renault-Shetlerville rests unconformably upon the Ste. Genevieve limestone, and this unconformity must represent a time interval not only equivalent to that between the Renault and Aux Vases in Monroe and Randolph counties, but a very much greater time during which the Aux Vases sandstone was deposited and also the time interval preceding the Aux Vases during which the underlying Ste. Genevieve and St. Louis limestones were solidified and their secondary chert formed, following which the whole of the Ste. Genevieve and a part of the St. Louis limestones were removed by erosion in some parts of the region. The unconformity represented by all of these events in Mississippian history must be considered as being of great importance in the classification of the Mississippian as a whole.

The limestones of the Renault are all more or less fossiliferous wherever they occur, and in some localities faunas of considerable magnitude can be secured. One of the forms which can be found with careful search, wherever good exposures of the Renault are present, is the crinoid *Talarocrinus*. This crinoid genus is represented by several species whose geographic distribution is somewhat different, but the same species is known to occur in localities as far apart as Monroe and Hardin counties. A peculiar feature of the genus is its two basal plates, and nearly all of the Renault species have the suture between the two plates somewhat impressed, giving to the base a distinctly bilobed form. These bases and the separated radial plates are the portions most commonly met with, and from these fragments the species cannot be certainly determined, but these bases alone seem to be sufficiently characteristic to be distinctive of the Lower Chester faunas, and they are much more commonly met with in the Renault than in the Paint Creek, the higher limestone unit of the Lower Chester. Another fossil form which is very characteristic of the Lower Chester beds, is the bryozoan *Cystodictya labiosa*, which occurs in both the Renault and the Paint Creek, but has nowhere been observed in any higher formation. The Renault fauna can be differentiated from that of the higher Paint Creek limestone, among other ways, by reason of the much less number of *Archimedes* and *Pentremites*, representatives of both of these genera being very conspicuous in the Paint

Creek while *Archimedes* especially, which is such an abundant form in most of the Chester faunas, is inconspicuous in the Renault in most localities, and in very many collections does not occur at all.

The basis for correlating the Renault across the entire state of Illinois, from St. Clair County to Hardin County, is not only the position of the formation in the stratigraphic column, but also the uniformity of the fossil faunas which occur in the formation. Every species which has been recognized in the Shetlerville-Renault faunas of the southern counties, with the exception of four which are wholly restricted, so far as known, to the Shetlerville beds of Pope and Hardin counties, are known to be present in the typical Renault of Monroe County, except one form which is known in the Paint Creek. Furthermore, the especial index fossils of the Ste. Genevieve limestone have nowhere been found in association with the Renault-Shetlerville fauna. While it is not possible in this place to enter into a discussion of the details of the faunal characters of the horizon, it can be said that most detailed studies of these Lower Chester faunas seem to establish without any doubt the paleontological correlation of the Renault horizon across the entire state.

The sandstone beds of the Renault are commonly less massive than those of the Aux Vases, and they not infrequently contain the fossil trunks of a species of *Lepidodendron*, while no fossils at all have been observed in the Aux Vases.

Yankeetown chert[1] *and Bethel sandstone.*[2]—Succeeding the Renault formation in the Monroe-Randolph County area in Illinois, there is a thin, but very peculiar and persistent bed, which has been called the Yankeetown chert. This formation is siliceous throughout, much of it is a true chert, but in many localities it is seen to include numerous sand grains and locally it is a quartzite. The bedding of the formation is exceedingly irregular and knotty in many places, but locally at least it is quite even. In many places the rock exhibits a distinct, horizontally banded appearance, the separate bands being slightly different in color and only a small fraction of an inch in width. As ordinarily seen in surface outcrops

[1] Weller, *Trans. Ill. Acad. Sci.*, Vol. VI (1914), p. 124; also *Ill. State Geol. Surv.*, Monog. I (1914), p. 25.

[2] Butts, *Mississippian Formations of Western Kentucky* (1917), p. 63 .

the Yankeetown is rather light colored, and it may be detected in many places by the presence of the fragments of nearly white chert scattered through the surficial deposits.

The thickness of the Yankeetown in the Mississippi River counties nowhere exceeds 20 feet, and in places it is perhaps less than 10 feet thick. In spite of its thinness, however, the Yankeetown is very persistent, and is uniform in its characters from a point in St. Clair County not more than eight or nine miles south of East St. Louis, to near Lithium in the northern part of Perry County, Missouri.

Where the Lower Chester formations reappear in Union County, Illinois, the horizon of the Yankeetown is occupied by a sandstone formation quite different in character from the Yankeetown, which has been named the Bethel sandstone by Butts from outcrops in Kentucky. This sandstone holds its position in the Chester section from Union County to Hardin County, except where the outcropping belt is interrupted by faulting, although in southern Johnson County there is a short interval where the formation is entirely lacking. In the first section in Union County, east of Anna, where the Bethel sandstone has been observed, its thickness is comparable to that of the Yankeetown in Monroe and Randolph counties. It is certainly not greater than 20 feet, and perhaps does not exceed 10 feet. Traced to the eastward across the southern counties to the eastern edge of Johnson County, the Bethel nowhere exhibits a thickness greater than 25 or 30 feet, and at one locality at least, in Johnson County, it is lacking altogether. In western Pope County the formation is interrupted by a great, down-dropped fault block, and where it is exposed to the east of this fault block it is considerably thicker, and continues to increase to the east, attaining a thickness of at least 100 feet in southwestern Hardin County.

This sandstone continues southward across the Ohio River into Kentucky, and it is this formation which Ulrich mistakenly considered to be the equivalent of the Cypress sandstone of Engelmann, an error which he has acknowledged and corrected in his latest contribution to the subject.[1]

[1] *Formations of Chester Series in Western Kentucky* (1917), p. 8.

Wherever the contact of the Bethel sandstone with the underlying Renault is exposed, there is evidence of unconformity between the two formations. In the Ohio River bluffs in southeastern Hardin County this contact is well exposed, the lower layer of the sandstone, 6 to 18 inches in thickness, is composed of fragmental material consisting of flat pebbles, slabs more or less irregularly disposed, much lime sand, quartz sand of large, rounded grains, with many fragments of fossils, some of which are worn and rounded. The actual line of contact between the two formations is uneven and undulating. At Indian Point, in southern Johnson County, the basal layer of the Bethel sandstone is a lime conglomerate with more or less flattened pebbles up to two or three inches in maximum dimension. The unconformity of the Yankeetown upon the underlying Renault in the Mississippi River counties, is suggested by the varying thickness of the Renault, and by the uniform character of the Yankeetown, resting in different places upon limestone, shale, and sandstone layers of the Renault.

The correlation of the Yankeetown-Bethel horizon entirely across the state must be based upon the correlation of the underlying and overlying formations, both of which are abundantly fossiliferous. No determinable fossils have anywhere been collected from the Yankeetown, and the invertebrates that have been found in the Bethel are a few very imperfect examples of common Chester types of brachiopods and bryozoans. This sandstone does contain, in places, numerous fragmentary plant remains, mostly tree trunks, of which the only form that can be identified is *Lepidodendron*, probably of the same type that was present in the sandstone layers of the Renault, and which is present in most of the Chester sandstones.

Paint Creek limestone.[1]—Overlying the Yankeetown and Bethel formations is the Paint Creek limestone and shale. In the Mississippi River counties, extending from St. Clair County, Illinois, to Perry County, Missouri, there is present in the lower part of this formation, a persistent bed of deep-red, non-laminated clay or shale, 12 to 15 feet in thickness. Between this red clay and the

[1] Weller, *Trans. Ill. Acad. Sci.*, Vol. VI (1914), p. 125; also *Ill. State Geol. Surv.*, Monog. I (1914), p. 26.

Yankeetown for a thickness of about 10 feet there is a series of bluish, calcareous shales with platy limestone layers, and above the red bed there are other calcareous shales which pass up into limestones, thinly bedded and shaly below, becoming more massive above, these beds being succeeded by more shale beds some of which are variegated red and blue in color. Although there are other reddish or at least variegated shale beds elsewhere in the Chester section, there is no bed anywhere in the series in Illinois that can be mistaken for the deep-red clay bed of the lower part of the Paint Creek formation. Not only is this bed recognizable in surface outcrops, but it can be easily detected in many well records.

The red shale bed of the Paint Creek formation outcrops at intervals throughout the Chester belt from St. Clair to Randolph counties, the northernmost exposure being about one mile northwest of Millstadt. The formation continues across the Mississippi River into Missouri, and the southernmost exposure is in northern Perry County of that state. Between these two localities the same red shale bed is exposed at many localities. It is exceedingly uniform in its characteristics, and where it is met with it is absolutely impossible to mistake it for any other bed in the Chester series.

The limestones of the Paint Creek formation are similar in lithologic character to many other limestones of the Chester series. The several beds are separated by shale layers varying in thickness from an inch or so to several feet, and the limestone beds themselves vary in thickness from less than one foot to three or four feet. Most of the shale beds are more or less calcareous, but above the main mass of limestone there is a considerable body of shale in many sections that is little or not at all calcareous, and is variegated red and blue or purple. Most of the limestone beds are crystalline, some are quite pure and white, others are more impure and much darker in color.

In the southern counties of the state, from Union to Hardin, the Paint Creek is represented mostly by shales, with only subordinate limestone layers, commonly very thin and exhibiting considerable variation in the entire amount that is present. The deep-red shale bed is wanting in the section in these southern

counties, but the shales that are present commonly weather into a red, residual clay which somewhat resembles the material in the red bed of the Mississippi River section. When not weathered, the Paint Creek shale of the southern counties is very fissile, breaking into thin, brittle flakes which are slightly olive green in color when dry, but appear quite black where the exposures are in situations where the rocks are kept constantly wet. In one locality in Johnson County a bed of somewhat variegated red and blue shale has been observed similar in character to some of the beds in Monroe County.

The limestone layers included in the Paint Creek formation in the southern counties vary greatly in character. In places some of these layers are very siliceous, some of them being little more than layers of sand firmly cemented with calcium carbonate, other layers are hard, dense, and compact with few or no sand grains, still other beds are quite free from silica, and some of them, at least, are more or less coarsely crystalline, dark limestone, quite like some of the beds in the more typical exposures of the formation in Monroe County.

The fauna of the Paint Creek is uniform in its essential features, through the full extent of the formation in Illinois. It has much in common with the faunas of the Renault, and the two formations together constitute the two fossiliferous horizons of the Lower Chester. The bryozoan *Cystodictya labiosa* is common in both horizons, as are the species of *Talarocrinus* with bilobed bases, but the Paint Creek fauna includes a much greater number, both of individuals and species, of *Pentremites*, and the bryozoan genus *Archimedes* is far more abundant than in the Renault. The same species of *Pentremites* are present in the fauna from St. Clair to Hardin counties.

The Paint Creek occupies the position in the section which was originally assigned to the Tribune limestone by Ulrich, though it is by no means the equivalent of the formation so named, at Tribune, Kentucky. More recently Butts[1] has proposed to substitute the name Gasper for Tribune, because of the unfortunate choice of

[1] Butts, *Mississippian Formations of Western Kentucky* (1917), p. 64.

that name for the formation by Ulrich. The Paint Creek is the equivalent of the higher portion, at least, of the Gasper limestone of Kentucky.

MIDDLE CHESTER GROUP

In passing from the Lower to the Middle Chester formations, the region of typical and more complete development is found to be in the more southern counties of Illinois, rather than in the Mississippi River counties. As in the case of the Lower Chester, the Middle Chester is constituted of four formations, two siliceous and two calcareous.

Cypress sandstone.—This is the formation for which Engelmann chose the name Cypress sandstone, from the exposures in the bluffs of Cypress Creek, Union County, but it is not the sandstone for which Ulrich used the same name in the report on "The Lead Zinc and Fluorspar Deposits of Western Kentucky."[1] The formation is continuously present in the Chester section from Hardin County at the east to Union County at the western extremity of the southern belt of outcrop of the formations. It is a very massive, cliff-forming sandstone, and except where it is interrupted by faulting in Hardin, Pope, and Johnson counties, it forms the upper portion of a nearly continuous escarpment across the state which is a conspicuous topographical feature. The formation is more uniform in its character throughout its extent in these counties than any other sandstone formation in the Chester series. Some other sandstones are just as massive and make just as conspicuous cliffs in places, but they do not retain such a character throughout for the reason that the massive portions of the other sandstones are much more interrupted, both vertically and horizontally, by thinly bedded and less resistent layers.

The lithologic character of the Cypress is similar to other sandstones of the series, or at least to certain portions of most of the other sandstones. It is rather fine in texture, yellowish brown in color, with more or less cross-bedding, although certain portions of the formation are conspicuously even-bedded, and in places, especially in the upper portion of the formation, the even beds

[1] Prof. Paper, *U.S. Geol. Surv.*, No. 36 (1905).

suggest the regular courses in a well-built masonry wall. The weathered surfaces of the cliffs become darker colored than the freshly broken rock, and in places more or less iron stained. The fossils of the Cypress sandstone consist of more or less fragmentary plant remains, the only recognizable form being *Lepidodendron* trunks.

It has not been possible to measure the exact thickness of the Cypress sandstone in any section in the southern counties of the state. The base of the formation, resting upon the Paint Creek shale, can be approximately determined in many places, but the top of the section in these same sections is in all cases missing and the upper portion has been more or less reduced by weathering. The greatest actual thickness that has been observed in a cliff is about 70 feet, but the thickness has been estimated as 110 feet in at least one section, and the average thickness across these counties is about 100 feet.

In tracing the stratigraphic position of the Cypress sandstone into the section of the Chester series of the Mississippi River counties, the sandstone is found to be much reduced in thickness and much less massive in character. In this section, as originally described by the writer,[1] a sand and shale formation overlying the Paint Creek limestone was named the Ruma formation. The later study of the section in the more southern counties has shown that the sandstone of the Ruma should be considered as the thinned-out margin of the Cypress sandstone, and that the shales below should more properly be considered as being a part of the Paint Creek. With this interpretation the name Ruma becomes superfluous, and Cypress may be extended to include these sandstone beds of the Ruma in Monroe and Randolph counties. In following the section still farther, into Missouri, it is found that the Cypress sandstone disappears entirely, and the super-Cypress limestones rest directly upon the Paint Creek.

In a recent contribution Ulrich[2] has proposed the correlation of the Cypress sandstone of the southern counties with the Lower

[1] Weller, *Trans. Ill. Acad. Sci.*, Vol. VI (1914), p. 126; also *Ill. State Geol. Surv.*, Monog. I (1914), p. 26.

[2] "The Formations of the Chester Series in Western Kentucky, and Their Correlates Elsewhere," *Ky. Geol. Surv.*, Plate D, opposite p. 47.

Okaw limestone of Monroe and Randolph counties. Such a correlation, however, is not supported by the evidence of the fossils and the faunal studies of the Chester have established beyond question the exact equivalence of the Golconda limestone of the southern counties with the Lower Okaw in Randolph County.

Golconda limestone.—When the Chester section in the Mississippi River counties was first elaborated by the writer, the name Okaw limestone was given to a thick series of limestones with shale partings overlying the so-called "Ruma" formation. It was recognized that this was probably a composite formation, and an attempt was made to map the higher beds as a separate unit from the lower ones, but this was finally abandoned because the heavy covering of drift seemed to make such a procedure impracticable. When the studies were carried into the more southern counties, it developed that the limestone beds equivalent to the Okaw were divided into two distinct units separated by an important sandstone formation. The lower of these two units has been named Golconda limestone from the excellent exposures in the Ohio River bluffs just above Golconda, in Pope County.

The Golconda limestone is constituted of a succession of limestone and shale beds, the details of which are commonly obscured by surficial material, and it is not known whether the details of the succession of beds are uniform throughout the areal extent of the formation. The limestone beds vary considerably in character, but in general they are of a light- or dark-gray color, and more or less crystalline in texture, with some layers oölitic. The shales are fully as variable and perhaps more variable than the limestones. Some of them are highly calcareous, while others are quite purely argillaceous; many of the beds are gray or buff, but others are dark and even black, and at a number of localities a layer of reddish shale has been observed. In the basal part of the formation there are shale beds with a considerable content of sand, and even some thin sandstone layers, but beds of this character are not present higher up in the formation.

In tracing the Golconda limestone into the Mississippi River counties, where it is represented by the lower and main portion of

the Okaw limestone, the characteristics of the formation remain much the same, although the local details are different. As in the southern counties there is a succession of limestone and shale members, but there is a larger content of limestone in the more western region. The limestone beds themselves are crystalline in texture, like those in the south, they vary in color from essentially white to dark gray, the lighter colors on the whole being more dominant in Monroe and Randolph counties, and the oölitic beds being much more conspicuous. The shale beds are similar in the two regions.

The establishment of the continuity and equivalence of the Golconda and the lower portion of the Okaw is based not alone upon their occupying an equivalent position in the section, but upon the paleontological characters as well. One of the notable horizon markers of this lowest limestone formation of the Middle Chester is the little brachiopod *Camarophoria explanata.* This species is unknown in the Lower Chester faunas, but is a common member of all the Middle Chester faunas, and is present, abundantly in places, in some of the Upper Chester formations. The horizon where it is first introduced in the section can be considered as being well toward the base of the Golconda limestone. In the southeastern counties of the state one of the most reliable guide fossils for the lower Golconda is the Crinoid *Pterotocrinus capitalis*, which is commonly represented by the "wing-plates" alone. This species has not been recognized in Randolph or the adjoining counties, but in this region the near basal beds of the lower Okaw are characterized by the presence of a peculiar and very unusual fauna, for the Chester series at least, composed very largely of small pelecypods and gastropods, including many Bellerophontids. Many of the species of this fauna are undescribed, and some of them are peculiar and extraordinary. In southern Johnson County, at one locality, a fauna has been collected from near the base of the Golconda, in which most of these peculiar basal Okaw species are present, and associated with them are many examples of the characteristic *Pterotocrinus capitalis.* This mingling of forms, so peculiar in character, is assumed to be sufficient evidence to establish the equivalent of the Golconda with the lower Okaw, and the

name Golconda may be extended to include the equivalent beds in Randolph and Monroe counties.

The lithologic character of the Golconda limestone is of such a nature that its contacts with the underlying and overlying formations are not commonly exhibited, and at no locality have both of the contacts been observed in the same section. This condition makes the determination of the thickness of the formation a matter of estimate. In the neighborhood of Golconda the interval between the top of the Cypress sandstone and the base of the Hardinsburg is about 150 feet, and as this is the interval occupied by the Golconda, an approximate thickness of 150 feet may be assumed for the formation. The thickness of the whole of the Okaw limestone in the Mississippi River counties is something over 200 feet, and of this total thickness the lower Okaw, which is the equivalent of the Golconda, includes approximately 150 feet, being about equal to the Golconda in its typical exposures.

Hardinsburg sandstone.—Overlying the Golconda limestone and resting upon it unconformably is an important sandstone formation which in many places is scarcely less massive than the Cypress. Butts has given the name Hardinsburg[1] to this formation from a Kentucky locality. In general appearance, texture, color, etc., the Hardinsburg closely resembles the Cypress, and in isolated outcrops not seen in relation to an underlying or overlying limestone, it would not be possible in many places to differentiate the two formations. The Hardinsburg, however, is somewhat less massive on the whole, and includes considerable amounts of more thinly bedded sandstones in places. In general the Hardinsburg is somewhat thinner than the Cypress, although it does have a maximum thickness of at least 100 feet. There are places, however, in the southern counties where the thickness does not exceed 30 feet, and the average thickness is probably about 60 or 70 feet.

In the Mississippi River counties there is no conspicuous sandstone formation which corresponds in position with the Hardinsburg in the southern counties. There is present, however, within the formation to which the name Okaw was originally given, a horizon marked by a discontinuous sandstone layer which in

[1] *Miss. Form. W. Ky.* (1917), p. 96.

places is as much as 10 feet thick, elsewhere being wanting altogether. This layer is best exhibited in the vicinity of Chester, in the outside prison quarry at Menard, between Menard and Chester, and just below Cole's mill in Chester. This sandy layer in the Okaw is undoubtedly the attenuated margin of the Hardinsburg sandstone which has its greatest thickness in the southeastern part of the state, for the limestone beds above it possess many faunal characters which unite them with the limestone formation overlying the Hardinsburg in the southern counties.

Glen Dean limestone.—The Glen Dean limestone is another formation that has been named by Butts from exposures in Kentucky.[1] In the southern counties of Illinois the formation resembles the Golconda in general character, being composed of interbedded limestone and shale layers, but in most localities the proportional amount of shale is much greater in the Glen Dean, in places nearly the whole of the formation being shale. Many of the limestone beds in the formation are similar lithologically to those of the Golconda, being gray in color and crystalline in texture for the most part, but locally certain of the layers are somewhat more dense and compact.

The Glen Dean has certain faunal characters that differentiate it rather sharply from the Golconda. One of the best index fossils is a species of bryozoan, *Prismopora serrulata.* Examples of this species are triangular in cross-section, with three faces bearing zoöecia, these prismatic zoaria dividing at intervals. This bryozoan is not entirely confined to the Glen Dean, for it has been observed rarely in the Golconda, and is not uncommon in the Vienna limestone, still higher than the Glen Dean, but it is far more common in the Glen Dean than elsewhere, and in places some of the limestone ledges of this formation are veritable *Prismopora* gardens. *Pentremites spicatus* is another characteristic form, which has not been observed outside of this formation, but it is far less common than the *Prismopora.* A number of other bryozoans and some other fossil forms are more or less conspicuous in this formation, which are nearly everywhere or entirely unknown from other Chester horizons.

[1] *Miss. Form. W. Ky.* (1917), p. 97.

In the Mississippi River counties the whole assemblage of fossil forms which characterize the Glen Dean formation in the southern counties has been found to be present in those beds of the Okaw limestone which overlie the interrupted sandstone horizon in the midst of that formation, and these upper Okaw beds may be correlated directly with the Glen Dean and this name may be extended to include these beds in the Randolph-Monroe County section.

The thickness of the Glen Dean in the southern counties exhibits some variation from a minimum of 40 feet to a maximum of perhaps 75 feet. In the thinner sections it is apparently the higher beds that are missing, due perhaps, to the erosion of the upper surface of the formation before the deposition of the overlying sandstone. The thickness of the equivalent beds in Randolph County is similar to that in the southern counties, the usual thickness commonly being about 60 feet.

[*To be continued*]

A CORRELATION OF THE PRE-CAMBRIAN FORMATIONS OF NORTHERN ONTARIO AND QUEBEC[1]

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In a paper recently published in the *Journal of Geology*[2] the writer correlated the pre-Cambrian formations of northern Quebec as well as facts obtained during the last ten years would permit. The formations most satisfactorily correlated were a number of scattered patches of sediments which had been given the local names Pontiac, Mattagami, Broadback, and Brock series. In composition, succession, structure, and external relations these scattered patches of sediments were deemed sufficiently alike to warrant substituting the general name Mattagami series for the local names. The position of the Mattagami series in the geologic column is shown in the following succession:

Mistassini limestone
    Unconformity
Diabase dikes
    Intrusive contact
Cobalt series
    Great unconformity
Granite
    Intrusive contact
Lamprophyre dikes
    Intrusive contact
Mattagami series
    Unconformity
Gabbro and anorthosite
    Intrusive contact
Granite-gneiss (around Lake St. John)
    Intrusive contact
Nemenjish series (Grenville series ?)
Abitibi volcanics (basalts, andesites, rhyolites)

During 1918 the writer had an opportunity to examine for the first time the Timiskaming series in the Kirkland Lake district of northern Ontario, and was so impressed by its similarity to the Mattagami series that further opportunity was taken in 1919 to investigate its relation to that series. The results indicate beyond any

[1] Published by permission of the Geological Survey of Canada.

[2] *Journal of Geology*, Vol. XXVII, Nos. 2, 3, 4, 5, 1919.

reasonable doubt that the Mattagami series and the Timiskaming series of Kirkland Lake may be correlated and grouped together under a single name.

LOCATION

The area of Mattagami series nearest to the Kirkland Lake district is the Pontiac area lying south of the National Transcontinental Railway between the Ontario-Quebec boundary and the

FIG. 1.—Index map showing location (hatched) of area dealt with in this paper

Bell River. Between the two districts lies the Larder Lake district, 12 miles in width. The three districts together form a narrow strip of territory about 130 miles from east to west, and 25 miles from north to south (Fig. 1). The shaded area in Figure 1 shows

the general location of this strip within which lie the sediments whose correlation is dealt with in this paper. The Timiskaming Northern Ontario Railway passes through its western end, affording access to the important mining center of Kirkland Lake through Swastika station, and to Larder Lake through Dane station. The only access to the Quebec portion of the area is by canoe from Lake Timiskaming, Larder Lake, or the National Transcontinental Railway.

PREVIOUS WORK AND CONCLUSIONS

Reconnaissances along easily accessible water routes were made as early as 1900 by W. J. Wilson,[1] W. G. Miller,[2] L. L. Bolton,[3] Walter McOuat,[4] W. A. Parks,[5] J. Obalski,[6] and J. F. E. Johnston,[7] but the first detailed work appears to have been that of Brock[8] and Bowen,[9] in 1908, at Larder Lake. In the four years following the whole of the area shown in Figure 1 was mapped in more or less detail by A. G. Burrows, and P. E. Hopkins,[10] E. L. Bruce,[11] M. E. Wilson,[12] R. Harvie,[13] and J. A. Bancroft.[14]

These writers have reached very different conclusions regarding the age and external relations of the sediments in this strip of territory. Burrows and Hopkins (1912) consider the sediments of Teck, Lebel, and Gauthier townships to be a single series of inter-

[1] W. J. Wilson, *Geol. Surv. Can., Sum. Rept.*, 1901, pp. 117A–130A; *Geol. Surv. Can., Mem. No. 4*, 1910.

[2] W. G. Miller, *Ont. Bur. of Mines, Rept. No. 14*, pp. 261–68, 1905; *Rept. No. 11*, pp. 214–30, 1902.

[3] L. L. Bolton, *Ont. Bur. of Mines, Rept. No. 12*, pp. 173–90, 1903.

[4] W. McOuat, "Rept. of Prog.," *Geol. Surv. Can.*, 1872, 1873, pp. 112–35.

[5] W. A. Parks, *Geol. Surv. Can., Sum. Rept.*, 1904, pp. 198–225.

[6] J. Obalski, *Mining Operations in the Province of Quebec*, 1906, pp. 5–27; 1907, pp. 42–56.

[7] J. F. E. Johnston, *Geol. Surv. Can., Sum. Rept.*, 1901, pp. 130A–143A.

[8] R. W. Brock, *Ont. Bur. of Mines Rept. for 1907*.

[9] N. L. Bowen, *Ont. Bur. of Mines Rept. for 1908*.

[10] Burrows and Hopkins, *Ont. Bur. of Mines Rept. for 1913*.

[11] E. L. Bruce, *Ont. Bur. of Mines, Rept. for 1912*.

[12] M. E. Wilson, *Geol. Surv. Can., Mem. Nos. 17, 39*.

[13] R. Harvie, *Report of Mining Operations in the Province of Quebec during 1910*.

[14] J. A. Bancroft, *Report of Mining Operations in the Province of Quebec during 1912*.

bedded conglomerates and greywackes folded into a tight syncline with vertical or very steep limbs. Miller correlates this series with a similar closely folded conglomerate near Cobalt, previously called Timiskaming series. They recognize that it is much older than the Cobalt series, since the latter is found in Grenfell Township, to the west of Teck, lying flat within a quarter of a mile of the folded Timiskaming. The Cobalt series is regarded as probably Upper Huronian or Animikean in age, and the Timiskaming as Lower Huronian.[1]

The sediments continue without interruption (Fig. 3) from Gauthier Township eastward into McVittie and McGarry townships (Larder Lake district), where they are described by Brock and Bowen (1907) and later by M. E. Wilson (1908–9) as consisting of slates, carbonate rocks, and greywackes interbedded with basic altered lavas and therefore as of Keewatin age. Some steeply dipping conglomerates found to the north and south of the slates and other rocks are mapped as isolated patches of Cobalt conglomerate deformed by local disturbance.

Some four miles to the east of Larder Lake there outcrops the sedimentary series named the Pontiac schists by M. E. Wilson. These are separated from the Larder Lake sediments by a band of flat-lying sediments belonging to the Cobalt series (Fig. 3). The Pontiac series has been described by M. E. Wilson and J. A. Bancroft as a series of interbedded conglomerate and greywacke, folded into a vertical position, overlying the Keewatin unconformably, and underlying the Cobalt series with great unconformity. The similarity of the descriptions of the Pontiac conglomerates and greywackes and the corresponding members of the Timiskaming series of Kirkland Lake is pronounced.

The geological descriptions which have been briefly summarized appeared to the writer to indicate either that some error had been made in the study of one of the areas, or that there was more there than any of the geologists had recognized. Under the latter hypothesis it was conceived that there might be two ancient sedimentary series in the district, one of which was the better developed in each area, and that a different one had been

[1] *Ont. Bur. Mines, Rept. No. 22*, pp. 123–27, 1913.

recognized by each set of investigators. To determine if possible which of these hypotheses was the correct one, the writer in 1919 visited Larder Lake and made a study of the part of the area in doubt.

INVESTIGATIONS AT LARDER LAKE (FIG. 2)

A conglomerate outcropping prominently on the Larder townsite was the first thing to attract the writer's attention. This conglomerate is mapped by Brock and Wilson as belonging to the

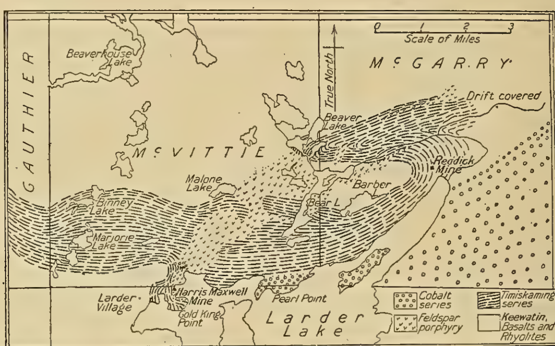

FIG. 2.—Larder Lake area

Cobalt series, but evidently with reservation on the latter's part, as he describes it thus:[1]

There is an area of mashed conglomerate on the north shore of Larder Lake, at Larder City, which has been intruded in a most complex manner by a hornblende lamprophyre, vogesite. *The pebbles of this conglomerate differ from the normal type* in that they consist entirely of quartz porphyry, rhyolite, and iron formation. . . . . The occurrence of the lamprophyre cutting the sheared conglomerate suggests that this conglomerate may be the equivalent of Dr. Miller's Timiskaming series.

Again, on page 37:

In the neighbourhood of Larder Lake there are numerous areas of conglomerate which have been greatly mashed in a direction parallel to the strike of the underlying Keewatin. These conglomerates might have any one of the three following relationships to the other rocks of the region: (1) They might be Keewatin conglomerates deposited between the volcanic flows of

[1] *Geol. Surv. Can., Mem. No. 17*, p. 38.

that series in a manner somewhat similar to the interflow conglomerates which occur in the lower portion of the Keewanawan series. (2) They might belong to an older Huronian series, that is, a series younger than the Keewatin but older than the *undisturbed* Huronian. (3) They might be portions of the ordinary flat-lying series which have suffered local disturbance.

Wilson concluded to map all the mashed conglomerates under the third hypothesis, as locally sheared Cobalt series. The only evidence in support is given on page 38:

It was also observed that in some outcrops where the mashed conglomerate has a considerable vertical thickness, the schistosity appears to diminish from the base upward, as if the contact of the flat-lying Huronian and the Keewatin might have served as a plane of deformation. This phenomenon can be seen in a conglomerate hill situated on the northern boundary of claim H.J.B. 21, in McGarry Township.

A plane of contact very commonly does function as a gliding plane during folding, so that the rocks close to it are apt to be more schistose than those farther away without regard to the age of the series; but the foregoing inference would be valid only if the schistose strata passed gradually into flat-lying beds, which they do not. The writer found that this conglomerate forms part of the conglomerate of the Timiskaming series.

To the east of Larder Village, across a small bay, Gold King Point projects into the lake. The greater part of this point is mapped as Keewatin on the early maps, with a small patch of conglomerate near the southeastern extremity; but the point was stripped clean of vegetation by fire three years ago, and the present exposures show clearly that the conglomerate is not a patch but a continuous band about 30 feet in width, dipping vertically and with its strike swinging from north 60 degrees west at the southeastern tip of the point to north near the Harris-Maxwell mine (Fig. 2). The conglomerate, like that on the Larder townsite, contains pebbles of basalt, rhyolite, jasper and iron formation. It is intruded by a feldspar porphyry like that of Kirkland Lake, and by dikes of lamprophyre. On the east side, where not intruded by porphyry or lamprophyre, it is in contact with massive basalt, exhibiting good pillow structure, and contains basalt pebbles. The rocks on the west of the conglomerate are not Keewatin, but well-bedded greywackes, showing fine lines of cross-bedding in

places; the dip and strike of the greywacke parallel those of the conglomerate.

It is evident therefore that these rocks, with those on the Larder townsite, are parts of a small tightly folded syncline, the axis of which has a north-south strike between the village and the Harris-Maxwell mine. It was also apparent that they lie unconformably on the greenstones, as the rhyolite, basalt, jasper, and iron formation are all members of the underlying volcanic complex.

A mile and a half to the east, on Pearl Point (Fig. 2) normal conglomerate and slate of the Cobalt series outcrops. The conglomerate is massive, at least 100 feet thick, and crowded with pebbles of all sizes. From 75 to 90 per cent of the pebbles are granite, the remainder other rocks. The conglomerate dips 15 degrees to 20 degrees, and is overlain by the normal argillite of the series, fine grained, black, and well bedded, containing an occasional pebble. The composition, succession, and structure of these rocks is so utterly different from those at Larder Village only $1\frac{1}{2}$ miles away that it is difficult to conceive them to be of the same formation.

Accordingly the writer returned to trace northward the band of conglomerate that passes across the Larder townsite. It runs somewhat east of north for about half a mile, then swings to the east across a drift-filled valley, on the other side of which it was easily picked up again and traced a short distance farther north, till, turning west, it passes beneath a large sand plain. Two miles to the west it has been mapped by both Wilson and Burrows on the shore of the Blanche River.

About half a mile to the north of the Harris-Maxwell mine (Fig. 2) an interesting set of relations occurs. The basal band of conglomerate, composed as before mainly of pebbles of rhyolite, jasper, and iron formation, here striking south 40 degrees east and with vertical dips, is overlain conformably on the east by interbanded greywacke and conglomerate, the conglomerates gradually becoming finer grained, passing into coarse grits and then into fine grits. Above the grits and greywackes occur some hundreds of feet of soft, slaty argillites, whose strike and dip parallel those of

the conglomerate. All these rocks are greatly broken up by intrusive dikes and masses of porphyry.

Lying on the upturned edges of these rocks is a second conglomerate, a massive rock composed almost entirely of greenstone fragments with about 10 per cent of granite pebbles, lying flat, and showing vague cross-bedding in places. This conglomerate occurs in irregular patches and knobs, evidently erosion remnants, lying indifferently on the older slates, greywackes, grits, and conglomerates. The writer concluded from the composition, which is characteristic of the base of the Cobalt conglomerate, and from the lack of deformation that it is an erosion remnant of the Cobalt conglomerate found to the east in larger masses; the areal relations to the underlying sedimentary series show that there is a large unconformity between the two.

The earlier geologic maps show a number of patches of conglomerate, mapped as Cobalt series, lying to the north of the areas of Larder slate, in many cases some distance to the north and within areas of Keewatin. These conglomerates proved on examination to consist invariably of beds dipping to the south at angles varying from 60 to 90, and frequently badly sheared. Their composition is like that of the conglomerate of the Larder townsite, in that the pebbles are largely of rhyolite, banded chert, jasper, and iron formation, with some basalt, although commonly the proportion of rhyolite is larger and that of iron formation smaller than on the townsite. The rocks to the north of the conglomerate band are invariably basalts except around Malone Lake, where rhyolite occurs; and almost invariably they exhibit pillow structures and other characteristics of lavas. The conglomerates were found to form, not isolated patches, but a strong band, continuous throughout the district, except where broken by intrusive masses of porphyry, and where, for a short distance to the east of Barber Lake, it has been obliterated by thinning and intense shearing.

The rocks to the south of the conglomerate band were then carefully examined, as some of them had been previously mapped as Keewatin. A great deal of excuse for the earlier mapping was found, in that in many cases the rocks are massive, dark green, chloritic rocks, indistinguishable in the average hand specimen

from the usual altered basalt. This is particularly the case in the area about 2 miles due north of Larder Village. But careful detailed examination showed that nowhere are there any ellipsoidal structures or amygdaloidal or other textures characteristic of lavas, although the massive character of the rocks indicates that these textures would have been preserved had they ever existed. On the contrary, bedding was observed at many points where exposures were clean and free from moss. Stratification is rarely prominent, but always distinct, being marked by slight changes in color, composition, and grain. It was clear therefore that these rocks are not lavas, but greywackes, presumably composed of the débris of eroded basalt flows. This conclusion was strengthened by finding in many places on clean weathered surfaces occasional angular or subangular grains of basalt.

Since these rocks are thus proved to be sediments, not lavas, the earlier conclusions as to the interbedding of the Larder Lake sediments with lavas become invalid, together with the conclusions drawn therefrom as to the Keewatin age of the sediments. As there is no observed unconformity between the different bands of sediments, it is concluded that they form a single series, infolded with the older volcanics into a tight syncline. This series of sediments rests unconformably on the Keewatin, since the basal conglomerate is composed mainly of Keewatin material, and is overlain with structural unconformity by the Cobalt series. It is intruded by feldspar porphyries and by lamprophyre dikes. Because of its stratigraphic position, lithological similarity, and geographic continuity (Fig. 3) the series is clearly a continuation of the Kirkland Lake Timiskaming.

Figure 3 shows the Timiskaming to be a strong band 1½ to 2 miles in width, with a general east-west trend. Less than 3 miles due east of where the band is concealed by the Cobalt series on the east side of Larder Lake, the Pontiac series outcrops, and continues as a strong band for another hundred miles eastward. J. A. Bancroft has shown that the external relations of the Pontiac series are identical with those of the Timiskaming series; both overlie the Keewatin with unconformity, are intruded by granites, and are overlain by the Cobalt series with great unconformity.

Both are deformed along east-west axes and the basal conglomerates of both are so similar that the writer has been unable to distinguish them. In view of these facts there can be no reasonable doubt as to the correlation of the two series. Since the Pontiac series has already been correlated with other ancient sediments of northern Quebec under the general name of Mattagami series, a general correlation of northern Ontario and

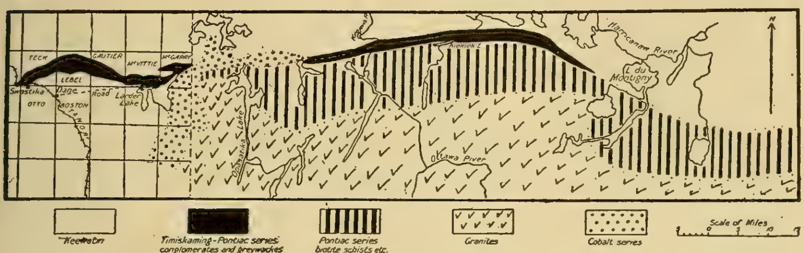

FIG. 3.—Sketch map showing the lineal distribution of the Timiskaming-Pontiac series in Ontario and Quebec.

Quebec is thus established. The name Timiskaming, which has priority, will henceforth be used in this report in referring to these sediments both in Ontario and Quebec, replacing the name Mattagami series.

ECONOMIC VALUE OF THE CORRELATION

The correlation thus established possesses a certain economic value which may now be briefly discussed. The writer has recently shown[1] that in the Matachewan district of northern Ontario valuable gold deposits have been formed through the action of juvenile solutions originating from a body of cooling syenite porphyry. Similar porphyries are found in many places through northern Ontario, and very commonly in association with gold deposits. While the genetic connection of the gold deposits with the porphyry has never been definitely proved, so far as the writer is aware, in any district but that of Matachewan, still the frequency with which the association occurs is extremely suggestive. The porphyries intrude the Keewatin volcanics in dikes, batholiths, and rarely sills; when they intrude the Timiskaming series the bedded

[1] *Economic Geology*, Vol. XIV (1919), pp. 281–301.

structure of the latter causes them commonly to assume the form of sills. Gold deposits have not as yet been found around the batholiths, presumably because the upper contacts, where juvenile waters might have deposited ores, have been eroded away, while the lower surfaces are not exposed. The porphyry dikes frequently have gold deposits associated with them, but it is commonly found that such deposits are small, presumably because the dikes are not large enough to have afforded any great amount of juvenile water. The most favorable form for the porphyry to assume would seem in theory to be the sill, which combines a large volume with a relatively small thickness, together with the exposure of both edges, in tilted rocks. The facts correspond with the theory, inasmuch as within the boundaries of the Timiskaming series, where the porphyries commonly form sills, gold discoveries have been very numerous, and many of the discoveries have been developed into producing mines.

The syenite porphyry is found in large amount throughout the Kirkland and Larder Lake districts, and was found by the writer in Quebec, to the east of the Larder Lake area, and also on Lake de Montigny, near the east end of the Pontiac area. It would seem likely therefore that it may be found intruding the Timiskaming series throughout its whole length of 130 miles although perhaps not in such volume as in the Kirkland and Larder areas. Thus the correlation between the Timiskaming and Pontiac series increases the Timiskaming area, already recognized as very favorable for prospecting, to four times its former known size.

EXTERNAL RELATIONS OF THE TIMISKAMING SERIES

Facts already briefly stated in the foregoing pages indicate that the Timiskaming series overlies the Keewatin unconformably, is intruded by granitic rocks, and is overlain with great unconformity by the Cobalt series. In view, however, of the disagreement that has existed in the past between those studying the districts under consideration, it seems advisable to enlarge somewhat on the previous statements.

Relations to the Keewatin.—The basal conglomerate of the Timiskaming series contains pebbles of all the volcanic series, as

well as a few pebbles of granite and syenite. The volcanics observed in the basal conglomerate include basalt, andesite, rhyolite, iron formation, red jasper, and various cherts and tuffs, many of them possessing well-defined bedding. Schistosity in the pebbles was observed in one place only, near Kenogami station on the Timiskaming and Northern Ontario Railway, where a few pebbles of a peculiar volcanic breccia are sheared. (This statement naturally applies only to such bodies of conglomerate as have not been sheared as a whole. Where this has taken place the pebbles are to be found in all stages of mashing.) The pebbles in the basal parts of the conglomerate are very well rounded, thus evidencing considerable wear before final deposition.

Wilson has argued that the presence of pebbles of the volcanics does not constitute proof of unconformity, and while he does not exclude the possibility of unconformity he regards it as possible that the conglomerates do not represent any long erosion interval. It is true that the presence of the lava pebbles is not full proof of unconformity, and the writer will go farther and admit that even the granite pebbles do not necessarily indicate unconformity, since he has found a few granite pebbles in coarse tuffs interstratified with Keewatin basalts. The conclusive evidence of unconformity is found in the presence of pebbles of iron formation, bedded chert, etc. These are water-laid sediments, as is clearly shown by their thin uniform bedding, their frequent association with thin-bedded tuffaceous clastics, and their association in other places with pillow lavas, which are now commonly recognized as subaqueous extrusions. The presence and association of these pebbles in the Timiskaming conglomerate indicates conclusively that before the conglomerate could have been laid down there must have been uplift, some folding, and erosion of the underlying rocks. Unconformity is thus proved.

Relations to the granites.—The relation of the Timiskaming series to the ordinary granite of northern Ontario that contains a great deal of free quartz is not yet known, as such granite is not found in contact with the Timiskaming series at any known point. But granites of this type intrude the Timiskaming series in northern Quebec. At the contacts the sediments are more or

less metamorphosed and recrystallized by the heat of the intrusive, and converted into hornblende and biotite gneisses, occasionally with development of some garnet. Dikes of granite and pegmatite pierce the sediments, and some blocks of the latter are found included in the granites often at considerable distances from the contacts. The included blocks are in all phases of digestion from sharp-angled fragments through phases in which the edges and corners have been partially or completely dissolved to phases in which the only remaining indication of a foreign mass is a vaguely outlined patch of material more micaceous than the surrounding granite. The contact of the granites and Timiskaming is different in degree, though not in kind, from a granite-Keewatin contact, in that it is a fairly sharp line, instead of being a wide zone of blocks of the older rock separated by dikes and masses of intrusive. This is undoubtedly due to the influence of the bedding of the Timiskaming series in controlling the intrusion.

The principal granitic rocks known to intrude the Timiskaming in Ontario are two: a grayish syenite in Lebel Township, and various bodies of syenite porphyry. The syenite body in Lebel Township is presumably, from its shape, a batholith; the porphyries may form fairly large batholithic masses, as in the case of the large mass north of Larder Lake, but more commonly they form smaller bodies the intrusion of which has been largely controlled by the bedding of the Timiskaming. They tend therefore to be sill-like in shape, although they may be observed to cut the bedding in numerous places. The chemical and mineralogical composition of the syenite batholith and the intrusive sills is so similar that there can be little doubt that they are but different forms of the same intrusive magma. The writer has not observed the contact of the Timiskaming series and the batholith in Lebel Township, but the mapping by the Bureau of Mines indicates that it is of much the same nature as the granite contacts in northern Quebec already described. The evidence of intrusion of the sills is more difficult to obtain, since the sills had practically no recrystallizing influence on the sediments, and rarely have a chilled edge, include blocks of sediment, or send off dikes into the sediments. The best evidence of intrusion is the areal evidence,

obtained by mapping. Thus in McGarry Township porphyry masses are seen (Fig. 2) to cut across the bedding of the Timiskaming near its base, into the underlying Keewatin. The same thing on a smaller scale may be observed to the north of the Harris-Maxwell mine, where masses of porphyry cut across the bedding of the sediments, from the conglomerates into the overlying greywackes and slates.

Relations to the Cobalt series.—The Cobalt series overlies the Timiskaming with very great unconformity. The relations of the two series are seen in two places. In Grenville Township, near Kenogami station, the flat-lying Cobalt series outcrops a quarter of a mile northeast of the Timiskaming, which dips 60 to 70 degrees. The Cobalt series outcrops again near the Timiskaming series at Larder Lake. As mentioned previously, a small outcrop of the Cobalt basal conglomerate north of the Harris-Maxwell mine was observed to lie on a peneplaned surface beveling the Timiskaming series and the porphyries and lamprophyres which intrude it. The Cobalt conglomerate here lies in turn on Timiskaming conglomerate, greywacke, and slate, which are tilted into vertical attitudes, as well as on the intrusives. The unconformity is thus clearly proved. The Cobalt conglomerate on Pearl Point (Fig. 2) contains numerous fragments of the greywackes, slates, and porphyries of the Timiskaming series. The Timiskaming therefore suffered intense folding, intrusion, and peneplanation before the Cobalt was laid down on it.

The thickness of strata eroded during the peneplanation which took place before the Cobalt series was deposited has never been estimated, but some data obtained in Boston Township permit of the calculation of a minimum figure. Careful observations made on the structure of the Keewatin in this district and elsewhere throughout northern Ontario and Quebec, show, wherever studied, that it has been thrown into close isoclinal folds, usually upright or slightly inclined, but occasionally overturned. Such a fold is illustrated in Figure 4. Erosion has cut so deeply into these folds as to remove the crests entirely, so that only the steeply inclined limbs may now be observed. In three or four places the writer has found good outcrops directly across the axis of such a fold,

and was thus able to observe directly that the width of the flattened strata along the axis was slight, perhaps 100 feet or thereabouts. It is clear therefore that the minimum amount of erosion necessary to produce such a condition, represented by *CC′* in Figure 4, can be determined by measuring the thickness of the strata by the usual methods. All that is necessary for such a determination is a knowledge of the position of the axis of an anticline and the next adjacent syncline, which may be observed directly or calculated from the position of some recognizable horizon.

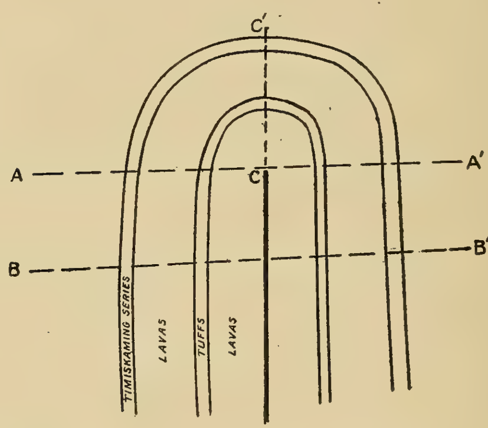

FIG. 4.—Diagram illustrating method of calculating minimum amount of erosion at the base of the Cobalt series.

It need scarcely be emphasized that such a determination of the amount of erosion is no more than a minimum, placing the erosion surface in the position *AA′* (Fig. 4). It gives no hint of the additional thicknesses of rock removed in the formation of any lower erosion surface *BB′*.

In Boston and Otto townships a recognizable horizon for purposes of measurement is afforded by a band of well-stratified tuffs approximately 1,300 feet in width which are here interbanded with the basalt flows (Fig. 5) This band was determined, by methods described,[1] to have the north side as the upper. In the

[1] *Jour. Geol*, Vol. XXVII (1919), p. 75.

south part of Boston Township there is a similar band, the upper side of which was determined by similar means to be the south. The bands are of about the same width, the southern one somewhat the wider, as it contains a larger proportion of interstratified basalt flows which could not be separated in mapping. There can be no

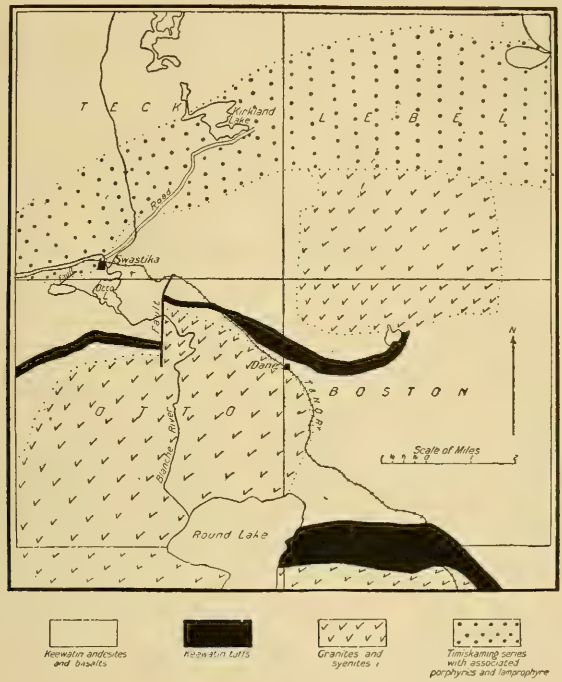

FIG. 5.—Sketch map showing the tuff bands in Boston and Otto townships and their relations to the Timiskaming series.

doubt therefore that the two bands form the limbs of an anticline whose crest has been cut off by erosion. The dips of the strata in both bands average about 70 degrees or higher. At their nearest point of approach the bands are about 17,000 feet apart, so that the axis of the anticline may be considered to be approximately 8,500 feet from the base of each band.

The syenite batholith to the north of the tuffs in Boston Township prevents the calculation there of the thickness of the Keewatin

between the tuffs and the Timiskaming series. About 5 miles to the west, however, in Otto Township, where the tuffs approach the Timiskaming most closely, there is a width of 8,250 feet between the base of the Timiskaming and the base of the band of tuffs. The sum of these two numbers, 8,500 and 8,250, therefore represents the minimum width of the Keewatin between the center of the anticlinal fold and the base of the Timiskaming. Assuming an average dip for the Keewatin of 60 degrees, which is smaller than the average measurement, we arrive at a minimum thickness for the Keewatin of approximately 15,000 feet.

Overlying the Keewatin there was at least 3,600 feet of Timiskaming series so that there were at least 18,600 feet of strata in all removed by erosion before the deposition of the Cobalt series. The actual amount may have been much more than this, however.

AGE

The descriptions of preceding sections show definitely that the Timiskaming series is post-Keewatin and pre-granitic in age, and antedates the Cobalt series by a period sufficient for the peneplanation of a mountainous area, with removal of at least 18,600 feet of rock. Its age may, however, be more closely delimited by the following consideration.

The Cobalt series outcrops in an almost continuous sheet from Larder Lake southwest to the north shore of Lake Huron. Throughout this whole section it lies in gentle open folds, with dips rarely exceeding 20 degrees, and rests on a correspondingly gently warped peneplain that bevels closely folded rocks cut by granitic intrusives. Near Lake Huron, however, this peneplain is directly overlain by the Bruce series, and the Cobalt series overlies the Bruce. There is an erosional unconformity between the Cobalt and Bruce series, representing a time interval sufficient for the removal of 1,700 feet of sediments,[1] but little or no structural unconformity; so that both series, where not disturbed by the Keewanawan folding and intrusion, lie in the same open gentle folds as the Cobalt to the north. It seems evident therefore that

[1] W. H. Collins, *Geol. Surv. Can.; Museum Bulletin No. 8*, 1914.

the Timiskaming, which forms part of the ancient, tightly folded, peneplaned basement must be pre-Bruce as well as pre-Cobalt.

W. H. Collins has recently shown that the stratigraphy of the Bruce series in Ontario is closely similar to that of the Lower Huronian of the Marquette region.[1] As the gap between the two districts is filled with Palaeozoic sediments this evidence is probably the best we shall ever obtain for the correlation of the Huronian of northern Ontario with that of the south shore of Lake Superior. Accepting it therefore, it follows that the Timiskaming series is pre-Huronian.

DESCRIPTION OF THE TIMISKAMING SERIES

In Teck Township the Timiskaming forms a syncline whose width averages pretty closely $1\frac{1}{2}$ miles, after subtraction of the widths of intrusive masses of porphyry and lamprophyre. The dip of the limbs varies from 60 degrees to 90 degrees. The maximum thickness, calculating the dip of both limbs at 90, is 4,000 feet; the minimum, calculating both limbs at 60, is 3,400 feet. Commonly the south limb dips 80 to 90 degrees, the north limb about 60 degrees. Calculated on this basis the thickness amounts to about 3,600 feet, a figure which probably approximates the truth. In the western part of McVittie Township, 15 miles east, where the whole width of the syncline is also exposed, the calculated thickness is closely the same.

In Teck Township the whole thickness is made up of interbanded conglomerates and greywackes. At the western end of the syncline near Kenogami station there is a basal band of conglomerate 400 feet thick, overlain by a massive greywacke containing an occasional pebble, the thickness of which is at least 125 feet, and may be much greater. About 3 miles to the east of this near Swastika, the basal conglomerate is over 1,000 feet thick. While there was not time available to make detailed sections of the Timiskaming of Teck Township, these observations, coupled with the alternating conglomerate-greywacke composition throughout the entire thickness, indicate pretty clearly that the sediments here are of subaerial origin, such as beach deposits, or continental

[1] W. H. Collins, memoir in preparation.

deposits from torrential streams; and that the beds, if worked out in detail, will be found to be lenticular in shape.

The basal conglomerate near Kenogami station is composed almost entirely of detritus from the underlying volcanic series. In a railway cut here it is in contact with a serpentinized agglomerate or flow breccia of very unusual composition and appearance. The conglomerate contains numerous rounded pebbles of this material, so that the fact of unconformity is indubitable. These pebbles are also slightly schistose, although the conglomerate and all the other pebbles are quite massive, so far as observed; so that some deformation must have preceded the deposition of the conglomerate.

The conglomerate is crowded with pebbles, particularly near the base where 75 to 80 per cent of the total mass is pebbles. They vary in size up to a foot in diameter, but the majority are from 1 to 4 inches in diameter. They are mostly pretty well rounded and worn. About half of them are longer in one direction than the other, presumably due to their original structure, and the long axes commonly lie parallel to the plane of bedding in the conglomerate. All the pebbles appear to be massive, with the one exception noted above. Approximately 50 per cent are of the light-colored cherty tuff which commonly accompanies rhyolite flows; some of these are probably also rhyolite. Thirty-five to 40 per cent are basalts and gabbros, the latter probably from the coarser-grained parts of basalt flows. The remaining 10 to 15 per cent consist of red jasper, banded chert, porphyry, and the peculiar breccia mentioned above, with here and there one of reddish granite and syenite. In the upper parts of this bed there is a somewhat greater variety among the pebbles. Quite a number are to be found of a quartz porphyry common among Keewatin rocks, and grayish granite pebbles are fairly common.

The matrix of the conglomerate is a rather coarse grit, composed of the small fragments of the rocks which supplied the pebbles.

The conglomerate is massive and unsheared. The stresses developed during the folding have been relieved, not by schisting, but by jointing accompanied by a number of small faults.

Many of the conglomerate beds lying at some distance above the base of the series, as in the second locality mentioned above

about 3 miles to the east of Kenogami, are markedly different from the basal beds, in that the pebbles are mostly small and very sharp angled, so that the rock at first glance gives the impression of a breccia instead of a conglomerate. Cross-bedding is frequently found here, and in general the beds are only a few inches or feet in thickness instead of being thick and massive.

The writer has been unable to make any personal examination of the Timiskaming in Lebel and Gauthier townships, but 12 miles to the east, in the western end of McVittie Township, the stratigraphy of the series is notably different from that described. The series in this third locality is well exposed on the north side of the syncline, on Binney Lake and eastward. On Binney Lake there is approximately 600 feet of interbedded conglomerate and greywacke at the base, striking north 80 degrees east and dipping 60 degrees south. The composition of the conglomerate is approximately the same as at Kenogami, but instead of being in thick massive bands it forms bands a few inches or feet in thickness, interstratified with greywacke. Only one heavy band of conglomerate was observed; it may be about 100 feet thick, and lies near the top of the conglomerate-greywacke complex. The remainder of the section is all massive, thick-bedded greywackes, except at the center of the syncline on Marjorie Lake, where there are some very impure quartzites, now partially altered to sericitic schists. The thickness of the latter was not measured, but is not over 500 feet at most. The total thickness along this section is about the same as in Teck Township, 3,600 feet.

The series maintains the same composition for about 2 miles to the east of the Binney Lake section, except that in this distance the central schistose quartzites become much purer and whiter. About 2 miles to the east of Binney Lake, however, and eastward past Malone Lake as far as Bear Lake the amount of basal conglomerate becomes much larger. The thickness of the basal part is perhaps not any greater than at Binney Lake, averaging about 600 feet; but instead of containing a great deal of greywacke, the whole thickness is of massive conglomerate, while occasional beds of conglomerate were also found in the greywacke for more than a quarter of a mile south of the main conglomerate band. Little can

be said of the remainder of this section, since the rocks above the conglomerate are broken and replaced by a large mass of intrusive porphyry. To the south of the porphyry on Bear Lake, however, a new formation appears, a thin-bedded argillite of about the same composition as the greywacke.

The basal conglomerate was next observed on the west end of Barber Lake, about a mile to the east of Bear Lake. In this distance it has thinned remarkably to only 60 feet. It is overlain by about 100 feet of rather impure sandstone, to the south of which lie the greywacke and argillites of the series. The thickness of the latter was not directly determined and cannot be estimated, since the southern edge of the syncline is covered by Larder Lake. The conglomerate band outcrops along the south shore of Barber Lake, continuing to thin, until about a quarter of a mile east of the east end it was observed to consist of about a foot of rather coarse grit. It was not found again on the south side of the anticlinal nose here (Fig. 2), so that the base of the series for at least half of a mile appears to be a rather impure sandstone. As this is very badly sheared, however, for a width of perhaps 25 feet from the contact, and converted into a featureless sericite schist, it is possible that pebbles may have existed in it but were obliterated.

On the north side of the anticlinal nose, the conglomerate reappears again, gradually thickening to about 30 feet. It consists, like that around Binney Lake, of thin pebbly beds interstratified with beds of greywacke. It maintains this character east of Beaver Lake, where the syncline (Fig. 2) pinches out. On the north side of this syncline, for a distance of about 2 miles east of Beaver Lake, the conglomerate is hidden by drift, and where it reappears it is a rather thin band, perhaps 30 or 40 feet in thickness, over which lies about 700 feet of rather impure quartzite. This is overlain in turn by a second band of conglomerate about 300 feet thick. To the south of this band of conglomerate the rocks are grits and impure quartzites, very poorly exposed. To the east, the lower conglomerate disappears entirely within a mile, replaced by beds of impure quartzite intruded by masses of porphyry. The total width of this mixture is 1,400 feet, of which about three-fourths is porphyry. To the south of this lies nearly 1,000

feet of interbedded argillite and impure sandstone, over which again lies some 250 feet of conglomerate with some interbedded impure quartzite.

The writer's attention has been called by Mr. M. E. Wilson to a peculiarity of some of the sheared conglomerates of the Larder Lake district, which here and there are found to contain squeezed, pebble-like masses distinguished by the presence of chrome-mica or fuchsite. Fuchsite is also characteristic of the altered and sheared porphyry masses of the region, and Wilson is inclined to believe that unconformity is thus indicated between the porphyry and the conglomerates. This, however, is obviously impossible, since, as already shown (p. 317), the porphyries cut the conglomerate and the other members of the sedimentary series. The writer made a careful examination of the composition of the conglomerate wherever it was found unsheared or only slightly sheared, but found no pebbles containing fuchsite. It seems indubitable therefore that the fuchsite in the pebbles of the sheared conglomerate must be formed during the shearing of the conglomerate after its deposition. Fuchsite is not alone characteristic of the sheared carbonated porphyry of the Larder Lake district, but it has been found by the writer in several places in Keewatin rhyolites and rhyolite tuffs which have been subjected to carbonate alteration and subsequent shearing. Pebbles of the Larder Lake porphyry are not found in the Timiskaming conglomerate here, but pebbles of rhyolites in all stages of alteration are common. It is likely therefore that some of these have given rise to the fuchsite pebbles in the mashed types of conglomerate.

The sediments were not traced farther to the east, as the next 2 miles is heavily drift-covered, and beyond this again the Cobalt series overlies. To the east in Quebec the rocks are described by J. A. Bancroft as follows:

> Exposures of a much metamorphosed conglomerate, arkose and greywacke appear at intervals on both sides of the (Kinojevis) river for about three-fourths of a mile. Either vertical or dipping very steeply to the north, and striking nearly east and west, these rocks may be traced to Keekeek lake and the upper portion of the river bearing the same name (about 16 miles). . . . . The conglomerate is chiefly composed of pebbles of Keewatin greenstone, although pebbles of granite and diorite are of frequent occurrence. Originally the

pebbles were well rounded and varied in size up to a foot across; they have been so flattened by pressure that today they possess lenticular forms. . . . . The matrix of the conglomerate as well as the arkose and greywacke have been quite universally converted into biotite schists; partially or completely recrystallized, yet repeatedly exhibiting their originally clastic character. . . . . That the sediments rest unconformably upon the Keewatin is evidenced by the pebbles in the conglomerate and the position which some of the exposures bear to those of the Keewatin.

M. E. Wilson described the sediments thus:

The Pontiac series in the district north of Kekoko and Kinojevis lakes is composed of greywacke, arkose, and conglomerate, which extends in an east-west belt having a width of about 2 miles. . . . . These rocks are all greenish gray or gray in colour, and have all been more or less mashed. The greywacke is everywhere recognized by the quartz grains which it contains. . . . . The arkose is of local extent and differs only from the greywacke in containing more fragments of acidic minerals. The conglomerate consist of mashed pebbles and boulders of granite, rhyolite, and quartz porphyry in greywacke matrix. No pebbles or boulders of basic rocks were seen.

Wilson also indicates on his map that the dips vary from 50 degrees north to vertical.

NEMENJISH SERIES (?)

In the writer's last paper on this subject[1] there were indicated some reasons for believing that a part of the body of sediments mapped as Pontiac series might in reality belong to an older sedimentary series which there were some reasons for believing to be of Grenville age. Briefly stated, these reasons were the absence of basal conglomerate at the east end of the sedimentary band and elsewhere, the occurrence of amphibolites in the Pontiac series, while amphibolites are not elsewhere found in the Mattagami (or Timiskaming) series, but are common in the Grenville and its supposed equivalents; and the occurrence of undoubted Grenville within 30 miles to the south and to the east. The facts described in this paper yield additional evidence on this point. The Timiskaming of Ontario is pretty uniformly about 3,600 feet in thickness through a band over 30 miles in length. As Figure 3 shows, in Quebec, 15 miles to the east, the band widens sharply to more than 10 miles, throughout which the dips average 45

[1] *Jour. Geol.*, Vol. XXVII (1919), p. 201.

degrees north except within 2 miles of the northern edge where they are steeply north or vertical. The dips of the northern edge are due to overturned folding, as the writer has shown.[1] If the series as mapped is all one, its thickness in Quebec is at least 22,000 feet, unless the outcrops have been repeated by folding; but Wilson records no southward dips. On the contrary, the width of the conglomerate-greywacke band, the descriptions of which correspond so closely with those of the Timiskaming of Ontario, is uniformly about 2 miles, or very little greater than that of the Timiskaming to the west. While it is possible therefore that the series does increase in thickness from 2,600 to 22,000 feet by depositional processes within less than 15 miles, the writer considers it more likely, in view of the other evidence, that only the band of conglomerate and greywacke along the north edge of the series as mapped is of Timiskaming age, while much or all of the biotite schists and amphibolite to the south of this band belongs to the older sedimentary series.

ORIGIN OF TIMISKAMING SERIES

The well-stratified nature of the Timiskaming sediments, especially of the upper members of the series, such as the argillites of Larder Lake, indicates that they have been laid down in a body of standing water. The well-rounded pebbles in the basal conglomerate indicate fairly long-continued wear, while the angularity of the fragmental material, in the beds above the proximate base, and its unsorted character indicate either that it has not been carried far before deposition, or else that if carried far the transportation has been very rapid, such as would be afforded by torrential streams from a mountainous area. The undecomposed character of the particles composing the greywackes, etc., indicate rapid removal of detritus after disintegration, such as occurs in any district where there is no vegetation to hold the rock particles in place long enough for decomposition to take place. The great thickness of the basal conglomerate in places and its rapid variations in thickness are characteristic of continental or subaerial deposits as also is the cross-bedding frequently to be

[1] *Ibid.*, p. 200.

observed in the conglomerates and interbedded greywackes. The change in the character of the sediments, from a series of interbedded conglomerate and greywacke on the west to a series on the east in which conglomerate is a relatively minor part, might indicate that the territory to the west which supplied the sediments was higher and more rugged, with more rapid streams, than that which supplied the sediments to the east. This conclusion is strengthened by the fact that the material composing the upper conglomerates in Teck Township is noticeably more angular than that to the east, so much so in fact that many of the conglomerates resemble breccias.

We may infer therefore a large lake or, on account of the thickness of the series, more probably a transgression of the sea due to gradual submergence. To the west of what is now Teck Township there must have been a fairly rugged mountainous or semi-mountainous area, flattening to the east. Vegetation was entirely lacking or almost so. As the sea advanced, a normal thin basal conglomerate was first formed, composed of fairly well-rounded fragments of the underlying rocks. This was supplemented by sharp-angled material brought down by streams, in large amount in the west, in lesser amount in the east. As submergence continued, the deposition of conglomerate ceased altogether in the east to be replaced by that of greywackes and finally argillites, with small amounts of arenaceous materials locally. Submergence apparently was never great enough to cover the mountainous area to the west; or, if so, with it disappeared the last source of sedimentary material in important amount; since the conglomerates and greywackes of Teck are not overlain by finer-grained beds.

NOMENCLATURE

A brief discussion of the nomenclature of the granite of Timiskaming district may be added here, as closely related to the main purpose of this paper. The term Algoman has recently been applied by Miller, Burrows, and others, when referring to granites intrusive into the Timiskaming series but underlying the Cobalt series.[1] The term Algoman was first used in the Rainy Lake district by A. C. Lawson, and was defined by him as applying to

[1] *Ont. Bur. Mines, Rept. No. 22*, Part 2, pp. 123–27, 1913.

granites intrusive into the Middle Huronian but underlying the Upper Huronian or Animikie.[1] The transfer of this term to Timiskaming district 500 miles to the east was made upon a correlation of the Cobalt series with the Animikie, since both series are flat lying and overlie a great unconformity, and a secondary decision that the Timiskaming, as a folded sedimentary series lying beneath the Animikean, was probably Lower Huronian. But with the determination of the Timiskaming series as pre-Huronian in age, while the intrusive granites are found in the Lake Huron area to underlie the Bruce or Lower Huronian, it is clear that the use of the term Algoman is entirely unjustified.

In its place the writer would apply the term Laurentian to these granites. This much-abused term has had an eventful history. It was first applied by Sterry Hunt in 1852 to what had up to then been known as the Metamorphic series, or lower pre-Cambrian. At that time these rocks were supposed to be all sedimentary, on the grounds that their gneissic textures were the remains of original bedding. They had been described in 1847 as consisting of a lower group of reddish and grayish syenitic gneisses, much contorted and generally at high angles, succeeded by an upper series containing important beds of crystalline limestone interstratified with the syenitic gneiss. The two groups were considered to be conformable. Between 1862 and 1865 the Laurentian, still supposed to be all sedimentary, was further subdivided into the Upper Laurentian, Labradorian, or Norian, in which subdivision were placed the great anorthosite bodies in the vicinity of Montreal, and the Lower Laurentian, which was further subdivided into the basal Ottawa Gneiss and the overlying Grenville series of interbedded crystalline limestones, quartzites, and gneisses. One of the first suggestions that part of these rocks might not be sedimentary but intrusive seems to have come from A. R. C. Selwyn, in the *Summary Report of the Geological Survey Canada* for 1877–78, but the first definite conclusion in this regard drawn from field observation is by Vennor, who reported in the director's *Summary Report of the Geological Survey of Canada* for 1879–80 that some of the anorthosites north of the St. Lawrence appeared to be intrusive in the crystalline

[1] *Geol. Surv. Can. Mem. No. 40*, p. 82. 1913.

limestones. Vennor, however, resigned from the Geological Survey in the next year and his report was never published. In 1885, A. C. Lawson published the results of his work in the Rainy Lake region, and demonstrated conclusively that the gneisses there, previously known as Laurentian, were not sedimentary rocks at all, but intrusive; and that, whatever the origin of the gneissic textures, they could not possibly be accounted for as relics of original bedding, since the rock had clearly been fluid enough at one time to permit of the movement through it of fragments of Keewatin. In 1887 he expressed the view that the foliation was due to flowage movements prior to complete solidification. He also considered that the granite gneisses represented the fused floor on which the Keewatin and Couchiching rocks had been laid down, and definitely reparated the term Laurentian to apply only to the intrusive gneisses. In the same year F. D. Adams anounced in the *Summary Report* that his study of the anorthosites north of the St. Lawrence River had shown that the gneissic and massive portions were gradational into each other, so that there was little doubt but that the whole body was of igneous origin. A second statement to the same effect was made by him in the *Summary Report of the Geological Survey* for 1891; but his full report on the subject was not published till 1894. A second report published in 1895 discusses the question of the Lower Laurentian in the district north of Montreal, previously subdivided into the Ottawa gneiss and the Grenville series; and shows that gneissic structures may have originated in many ways other than by original bedding, and that much of the gneiss here, particularly the Ottawa gneiss, is of igneous origin, although gneisses are present also whose composition indicates that they are altered sediments.

From this time it was generally recognized that the granite gneisses are of igneous origin, not sedimentary, and as the sedimentary parts of the old Laurentian series were already known in the literature as the Grenville series, the name Laurentian was restricted to its granitic parts. In many places, particularly in Canada, the name was indiscriminately applied to any pre-Cambrian granite of unknown age; but south of Lake Superior,

where careful detailed geologic work was being done following the discovery of the great copper and iron deposits, it was applied more rigidly only to granites unconformably below the Lower Huronian. In 1905, the International Committee on pre-Cambrian nomenclature defined the term Laurentian as applicable to "the granites and gneissoid granites which antedate or protrude through the Keewatin, and which are pre-Huronian." They added, "In certain cases this term may also be employed, preferably with an explanatory phrase, for associated granite of large extent which cut the Huronian or whose relations to the Huronian cannot be determined."

From 1905 to the present time the term Laurentian has gradually fallen into disuse in Canada. Careful detailed geologic work has been carried on in this period by the Geological Survey, with the use of local names to designate formations, and without any attempt at general correlation until all the necessary evidence has been obtained. In general, no names whatever have been applied to the granite masses, although Miller has called the granite around Cobalt the Lorrain granite. But with the writer's work of last summer, which completed the mapping of a large nuclear area in Ontario and Quebec, and brought in the evidence necessary for correlation and age determination, it appears possible to apply the term Laurentian correctly and rigorously.

The writer suggests that the term Laurentian be defined, in the more rigorous sense intended by the International Committee, to apply only to those granites and granite gneisses which intrude all rocks below the peneplain at the base of the Lower Huronian. Older granites, which will undoubtedly be found some day since the Timiskaming series contains granite pebbles in places and granite pebbles are found in Keewatin tuff beds occasionally, must receive other names when found. Laurentian will therefore apply to all granitoid masses intrusive into the Timiskaming series, and cut off by the peneplain which bevels it. This use of the term for northern Ontario corresponds to the usage in the Marquette district, the nearest pre-Cambrian on the south shore of Lake Superior; where the Laurentian granite is that which underlies the Lower Huronian.

SUMMARY

The present paper is a continuation of that published last summer. Data obtained during the summer of 1919 have shown that the sedimentary rocks at Larder Lake, Ontario, are not interstratified with the Keewatin, as formerly supposed, but are parts of a synclinal sedimentary series overlying the Keewatin unconformably. The series forms a lineal continuation of the Timiskaming series of Kirkland Lake, to the east.

It is shown that the Timiskaming series of Kirkland and Larder Lakes is to be correlated with the Mattagami series of northern Quebec. The name Timiskaming series is applied to both.

The age of the Timiskaming series is discussed, and the conclusion drawn that it is pre-Huronian.

Descriptions as detailed as possible are given of the stratigraphy and thickness of the Timiskaming series, and the mode of origin of the series is discussed.

As the determination of the age of the Timiskaming is also indicative of the age of the granites which intrude them, a brief consideration is given to the question of the proper nomenclature to be applied to these granites. The conclusion is reached that they may properly be termed Laurentian.

THE JUAN DE FUCA LOBE OF THE CORDILLERAN ICE SHEET

J HARLEN BRETZ

There were two large glaciers in western Washington during the latest, or Vashon, glaciation of that region. Each was essentially an elongated lobe of the great piedmont glacier which accumulated between the mountains of Vancouver Island and the British Columbia mainland. One lobe moved southward into the Puget Sound depression, filling it completely and pushing over into the Chehalis Valley to the south. The other moved westward through the Juan de Fuca Valley, extending as a tidewater glacier into the open waters of the Pacific Ocean. Though both of these lobes were augmented to some extent by valley glaciers from mountains in Washington, neither were true piedmont glaciers of these mountains.

Ice from this piedmont glacier in the depression now occupied by Georgia Strait moved almost directly south over the San Juan Islands, striating and grooving rock surfaces from tide-level virtually to the summit of the highest peak of the islands, 2,400 feet A.T.

In Fuca Strait south of the islands, the ice divided into two parts, one continuing southward as the Puget Sound Glacier, the other being deflected to the west and north of west as the Juan de Fuca Glacier. The Puget Sound Glacier pushed as far south as latitude 46° 50′ N., about 80 miles south of the re-entrant angle between the two lobes. Its extra-morainic outwash extended down the Chehalis Valley to the head of Grays Harbor, 30 miles beyond the limits of the ice.[1]

The Juan de Fuca Glacier extended westward along the southern coast of Vancouver Island nearly to Cape Beale[2] and spread

[1] J H. Bretz, "Glaciation of the Puget Sound Region," *Washington Geological Survey, Bulletin 8* (1913).

[2] C. H. Clapp, "Southern Vancouver Island." *Canada Geological Survey, Memoir 13* (1912), p. 144.

out as a broad spatula over the low-lying northwest salient of the Olympic Peninsula south of the strait. It reached westward nearly or quite to longitude 125° W., 10 or 12 miles off the Washington coast beyond Cape Flattery.

There is a narrow foreland between the Olympic Mountains and Juan de Fuca Strait, composed largely of Pleistocene materials. It is separated from the coastal plain west of the mountains by a group of ridges which strike parallel to the shore of the strait. They extend from Crescent Lake to the extremity of the Olympic Peninsula. They are everywhere several hundred feet high and certain summits are mapped as high as 4,000 feet. They serve as a divide between Soleduck River on the south and the short streams tributary to the Strait on the north.

The foreland terrace north of these ridges gradually narrows westward until it disappears, while the valley on the south side, between the ridges and the main mass of the Olympics, broadens and joins the coastal plain facing the Pacific.

The slopes of these ridges bear little or no glacial drift but the valleys between them contain deposits of Vashon till. The till of the foreland and in these valleys is, in general, light in color and contains plentiful granitic material, very much like the Vashon till of Puget Sound. Many erratics are of identical material. It seems clear that the débris was brought from the same feeding grounds north of the international boundary line.

But west of Crescent Lake and south of these ridges, the drift contains a large amount of basalt and dark-colored sandstone and conglomeratic débris which came from the Olympics immediately to the south, and which is not found in the till north of the ridges.

The eastern portion of these ridges apparently served as an imperfect barrier in the Juan de Fuca Glacier between drift from the distant Georgia Strait and from the nearby Olympics. Farther west, however, the ridges were overridden by the northern ice which carried its granitic drift southward almost to the mouth of Quillayute River.

The coastal plain of the Olympic Peninsula is densely forested. There are few roads and clearings. Such as do exist are along the streams. These conditions have forbidden any attempt to trace a

FIG. 1.—Approximate outline of the Juan de Fuca Glacier at its maximum

terminal moraine, and the limits of the Juan de Fuca Glacier as shown in Figure 1 are only approximate.

Glacial till is exposed at the junction of Beaver Creek and Soleduck River, near Pleasant Lake. It is dark gray in color, and contains some finely striated and faceted pebbles. Several granite pebbles, like those in the typical drift of Puget Sound, were found here.

Many bowlders, some of them finely striated, are scattered along the road from Pleasant Lake to Forks, and from Forks almost to Mora at the mouth of Quillayute River.

Granite bowlders with a maximum diameter of 5 feet lie in coves between rocky headlands along the beach immediately north of the mouth of Quillayute River. Their situation and their size render it highly improbable that they traveled along the beach for any considerable distance. The occurrence of granite bowlders here, and between Forks and Mora, indicates that the Juan de Fuca Glacier probably pushed south of the latitude of Cape Johnson.

Two miles north of Cape Johnson there is a sea cliff of glacial till, 25 feet high. The till is light colored and has many pebbles of the same kinds of rock which give Puget Sound drift some of its conspicuous pebbles. The fresh gray color and the shallow oxidized zone above it indicate the Vashon age of the deposit. It is material derived unquestionably from the feeding grounds of the great piedmont glacier whose bifurcation formed both the Puget Sound and Juan de Fuca lobes. Material from the Olympics is either lacking or a negligible quantity. The deposit apparently lies in a pre-Vashon valley whose northern portion contains Ozette Lake.

Between this place and Cape Flattery, at the extreme northwestern tip of the Olympic Peninsula, there are several such sections of till in the sea cliffs. There are also exposures of outwash gravel derived from the same source. The Juan de Fuca Glacier, composed of ice from Georgia Strait, clearly pushed out beyond the present coast. On Vancouver Island it reached at least 15 miles farther west than the longitude of Cape Flattery. Valley trains indicate that the sea stood 30 feet or so above tide at the time of this glaciation. The Juan de Fuca Glacier therefore must have possessed

a tidewater front from a point east of Cape Beale on Vancouver Island to Cape Johnson on the Olympic Peninsula, a distance of about 60 miles. Only Greenland and Antarctica today possess tidewater glaciers of comparable extent. Figure 1 shows the proportions of this lobe and the probable greater deployment at the mouth of the strait, along which the greatest movement of ice doubtless occurred.

The wastage of the Juan de Fuca Glacier was largely by bergs, notably in contrast with that of the glacier of Puget Sound which terminated at its maximum wholly on a land surface. Only the southern margin of the Juan de Fuca Glacier terminated on the land, and only in such a situation could outwash deposits be made at the maximum extent of the ice.

The area invaded by the southern portion of the Juan de Fuca Glacier is drained by Quillayute River. This stream and its tributaries on the coastal plain flow through young valleys cut some 50 feet into a great valley train which extends from Forks to the ocean. At Mora, the altitude of the surface of the valley train is about 30 feet above tide.

At Forks Prairie on the valley train, the gravel is more than 100 feet deep, and wells drilled here have encountered many large bowlders distributed throughout the gravel. Quillayute Prairie, between Forks and Mora, is an isolated plateau-like portion, a few square miles in area and from 75 to 135 feet above the surface of the surrounding plain. It is composed of gravel but has an irregular surface in its northeastern part, strongly suggestive of the presence of blocks of ice during its building. Its isolated position apparently is the result of dissection of an earlier valley train of which it is a portion. From the evidence of the irregular topography in the northeastern portion, the terminal margin of Juan de Fuca Glacier is here mapped as reaching Quillayute Prairie.

A valley train extends down the Soleduck Valley from the base of the Olympic Mountains and joins this broader tract beyond the limits reached by the glacier. The gravel of which it is composed is dark in color, and was derived largely from basaltic rocks and dark-colored sedimentaries. This is typical of most of the débris from this portion of the Olympic Mountains. But scattered

through it are numerous light-colored granitic pebbles and cobbles, which were brought by the Juan de Fuca Glacier over the divide between the Straits and Soleduck River. The Soleduck Valley train was built after the front of the ice had withdrawn eastward to a position somewhere near Lake Crescent. Indeed, aggradation from Olympic débris alone may have continued long after the Juan de Fuca Glacier had retreated entirely from the Soleduck drainage.

The thickness of the Juan de Fuca Glacier was sufficient to enable it to cross the divide between the Straits and the Soleduck valleys. The British Admiralty chart shows summits in this range 4,000 feet high, but the crest in general can hardly average 2,000 feet. Enough of the range was overridden to allow a continuous glacier to spread out on the coastal plain to the south, as shown in preceding paragraphs. Better figures on the thickness of the glacier are to be obtained from features of the Elwha Valley, a few miles east of Crescent Lake.

No granite is known *in situ* in the Olympic Mountains. "Float granite" however occurs in the lower portions of several Olympic valleys draining to Puget Sound and Fuca Strait, and very probably has been derived from Cordilleran ice which pushed up on the flanks and back into the valleys of both the eastern and northern sides of the Olympics.

The river gravel of the Elwha Valley contains scattered granitic bowlders and cobbles at least as far up as Elkhorn Ranger Station, 15 to 20 miles by valley from the Strait. Granitic erratics are abundant along the trail some hundreds of feet above the valley bottom at least 15 miles south of the Strait.

No lobe of ice from the northern glacier could have pushed this far up the narrow Elwha Valley from the lowland occupied by the Juan de Fuca Glacier, and if these bowlders record the presence of ice originally from Georgia Strait, the thickness of the Juan de Fuca Glacier must have exceeded the height of the ridges it had to cross. Hurricane Hills, the highest ridge directly in the path of such invading northern ice, attains an altitude throughout its length of 5,000 feet. Juan de Fuca Strait to the north is 600 feet deep. The Juan de Fuca Glacier opposite the mouth of the Elwha Valley therefore must have been more than a mile thick. This is

70 miles back from the front of the glacier, and indicates an average gradient of its surface of at least 80 feet per mile for that distance. It is probable that the front, which terminated in the open Pacific, was cliffed, and that this gradient must be reduced accordingly.

Based on similar evidence, the surface gradient of the Puget Sound Glacier averaged at least 47 feet per mile for 50 miles back from its front. In both cases, these are but minimum values for the thickness and gradient.

Acknowledgments are due to the Washington State Geological Survey under which the field work was done on which this paper is based.

"SLIDES" IN THE CONEMAUGH FORMATION NEAR MORGANTOWN, WEST VIRGINIA

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OUTLINE

FOREWORD

The purpose of this paper is a systematic discussion of "slides" in and near Morgantown, West Virginia. The abbreviation of the term "landslides" is in accordance with common usage in this locality, slides being a familiar term of everyday speech, so common is their occurrence. Either designation is somewhat of a misnomer as movements are not limited to true sliding.

As this article has a somewhat local bearing the general literature of the subject will not be quoted, though it is but just to state that the writer has received from this source some hints which have helped him in interpretations and comparisons. He

must, however, express his indebtedness to the reports of the West Virginia Geological Survey; also to Professor S. B. Brown, his colleague and chief, who has spent much time in acquainting him with the area. He is especially obligated to Dr. I. C. White, state geologist, and to Mr. David B. Reger, assistant state geologist, for their thoroughgoing review of the paper and constructive criticisms which have been freely used in its revision.

The slides studied occur in the Conemaugh Formation of the Pennsylvanian epoch. This is a series of alternating beds with shales predominating, in this locality approximately horizontal. The total thickness outcropping averages about six hundred feet. All shale members when exposed a short time to weathering agencies break down, if sufficient water is present, into a slippery, claylike mud. This creeps, slides, or even flows until the angle of repose is attained.

Slides, in the aggregate, constitute one of the big factors in the base-leveling of the area. Where numerous they produce a typical topography with features resembling those produced by glaciation and drainage. Less prominent forms frequently associated with slides are the "hoodoos" and ice pinnacles.

The Conemaugh is in a measure representative of several later formations of the Carboniferous, which show closely corresponding topography over much of the northern part of the state where such shaly sediments prevail.

While a single slide is rarely responsible for any great damage, in the aggregate slides become very effective. The total direct and indirect loss amounts to a heavy toll yearly. Some of the damage may be prevented by proper precautions, but the problem is too big for the adoption of absolute preventive measures.

GEOGRAPHY

The area studied with reference to slides is in Monongalia County, West Virginia, about five miles south of the Pennsylvania boundary. Morgantown may be considered the center. Through the area winds the Monongahela River. The Indians recognized the unstable character of the lands adjacent to the Monongahela by this name, which translated means "River of the Caving Banks."

The region is one of mature topography, with a relief averaging about five hundred feet.

GEOLOGY

The geologic maps of the State Survey show exposures in Monongalia County of Carboniferous formations succeeding toward the northwest in approximately parallel belts. The Monongahela River is here practically confined to a course in the Conemaugh, with its valley walls usually showing exposures of most and sometimes all of this formation.

The members of the Conemaugh are approximately horizontal at Morgantown. Elsewhere the dip is prevailingly toward the northwest with interruptions by mild anticlines and synclines. While a decided dip would undoubtedly have some influence on slides, it is believed for the purposes of this paper that the exposed areas of this formation may be considered as horizontal.

The Conemaugh is composed of alternating beds of shales, sandstones, coals, and limestones, with a total thickness varying from five hundred to six hundred feet. Shale and sandstone members vary from a few feet to over fifty feet in thickness. About four feet is the usual maximum for coal or limestone members.

SLIDES

ORIGIN AND EXTENT

Three factors may be considered necessary for the slides discussed. There must be a material which will take the proper consistency, slope, and water. Any of the Conemaugh shales may furnish the material. The degree of slope necessary is practically indeterminable, this varying with water content, thickness, and stratigraphic position of the shale. In extreme cases movements of the more fluid type will take place on nearly horizontal surfaces.

The shales generally are quite fissile, jointed, and slickensided, and tend to become saturated with water, the downward movement of which is successively impeded by the less pervious beds. This water evidently has little effect on the stability of the shales where they are not exposed to the air and excessive temperature changes. Cuts exposing unweathered shales show that these will

hold nearly vertical positions until effectively weathered, which may take from one to several seasons. Under the combined influence of the oxidizing action of the air, water, and temperature changes, especially freezing when water laden, the shales are shattered and comminuted until a slippery claylike mass is produced. Deep freezing is temporarily effective in stopping slide movements, though the result when thawing is a hastening of the process, as the mass more readily breaks away after the aid given by the expansional and contractional movements of freezing and thawing.

The transverse strength of a weathered shale mass is much less than that of the parent body, and when such a mass is sufficiently weighted with water it tends to break away from the latter and so originates the slide. With the breaking away a comparatively fresh surface of the shale is again exposed, so that the process is free to continue indefinitely at the same point or at least until an equilibrium between gravity and tenacity of materials is attained.

Weathered shale on drying becomes hard, and shows no tendency toward movement except in loose surface material.

TYPES AND DYNAMICS

Slides in the Conemaugh may somewhat arbitrarily be divided into three classes, (1) primary, (2) fluid, and (3) dry. These shade into each other or may combine.

1. *Primary.*—These are slides in which the moving mass is highly saturated with water and of the consistency of a thick mud. The primary slide is the first to form and decidedly the most important in totality of effects. The movements are rarely observed though it is believed movements fast enough to be visible are of not infrequent occurrence. Results may often be noted daily in active slides. A new movement of this sort is heralded by a break in the sod, the break tending, with occasionally marked variations, to follow a contour line. The position of this break is further affected by the relative toughness of the sod. Paths, since sod is weak or lacking, offer lines encouraging breaks. A single break is rarely of great linear extent, but the whole face of a hillside may be at times seamed with them. These breaks really

mark a variety of fault plane, the heavily weighted and weakened masses, impelled by gravity, breaking away and slowly dropping and sliding from the parent body. The movement tends to churn the mass rendering it more fluid so that later motion, still unobservable, has apparently an element of flowage. As the slide progresses, the face left bare by its movement widens, sometimes to many feet. This face has usually a much steeper gradient than the mass which previously covered it, offering a ready point of attack by the elements and gravity, so that by repetitions of the sliding process, one starting at the base may be responsible for a successive series to the top of a hillside.

As these slides are closely associated with the ground water, new breaks often show this exuding from their surfaces, their originally somewhat fissile faces soon slaking to a mud-plastered effect. The ground water may be sufficiently abundant to form a stream previously non-existent, which in turn may channel a gully that will determine the drainage flow of the immediate area.

In the same way that slides originate in the fresh shales, later slides repeatedly affect the masses of earlier slides, the process being active only when the material has ample water content.

As an explanation of the common terrace form resulting from slides, the following is suggested: Movement of the slide mass favors its drainage, and when sufficiently drained movement ceases. As drainage is most effective at the front, forward movement lags or ceases at that point first. By pressure of the still undrained rearward mass, the front in its resistance may be forced upward. The result is a hummock with a bare and steeply sloping front, a top of gentle slope which may be even roughly level or dip back toward the hillside, giving favorable conditions for ponding of water and further slide movements; at the rear, the bare steep slope marking the upper border of the surface from which the slide has broken away.

Whether by weakening of their support due to slides on the downslope side, or a crowding due to a faster movement on the upslope side, trees under their influence usually tend to incline downhill. As the roots are anchored in unstable earth, the unbalanced condition of the tree further accentuates this tendency.

When the forward frontal movement ceases or slows the upward crowding of this part may restore any trees upon it to a normal position or even to one inclining uphill. Occasionally trees may be seen inclining uphill on rather steep slopes. The slides producing this result are possibly of greater extent, with less differential and more rapid motion, and a counteracting tendency due to the inertia of the tree, most effective in its upper portion. Leaning trees are not as numerous as one might expect. This is largely due to the fact that they hinder slide movement. Thickly wooded hillsides rarely show such movement.

The vegetation on a slide frequently continues growing as though undisturbed. Between successive seasons of movement the breakage surfaces may become sod covered. Hillsides showing an almost kaleidoscopic change of surface may nevertheless be covered most of the time with a mat of vegetation.

Other things being equal, the thicker a shale the more subject it is to slides, although a thin shale underlain by particularly impervious material may be as troublesome as a thicker layer less favorably situated.

The intervening layers of other rock between shale beds frequently furnish a hindrance to the progression of slide movements uphill, as well as serving to initiate independent slide movements. Such layers, undermined by slides, will in time break off in blocks of size determined mostly by the joint and bedding planes.

2. *Fluid.*—This, the second type of slide, may be considered as an extreme stage of the first. In this type the proportion of water is so great and so thoroughly mingled with the shale mass, that the whole goes downhill in usually visible motion, like a thick fluid. On reaching a surface of sufficiently gentle slope, the heavier materials spread out and settle, leaving the water to drain away from the edge and over the surface like distributaries. These slides, like the third type, are not of great significance.

3. *Dry.*—The dry, or third type of slides, are those with a true sliding or rolling movement downward. On slopes barren of vegetation, movements in the material and drying may so loosen the surface covering, especially of shale flakes, that portions of this will move down in the manner stated unless checked by obstacles

or a lessened slope. If the obstacles are not sufficiently resistant, they may be loosened and may also move forward. Slides of the dry type are frequently observable as an aftermath to the slide movements of the first or second types, which are usually responsible for the barren surfaces upon which the third type originate. Generally the sliding mass is very small in bulk so that this type is probably the least effective in total results. Inasmuch as all the slides in these shales are primarily caused by water saturation, these dry slides are merely secondary effects, tending to re-establish the disturbed angle of repose.

TOPOGRAPHIC FORMS PRODUCED BY SLIDES

Several topographic forms have already been suggested, but it was thought desirable to classify together those which simulate the forms produced by other agencies.

RESEMBLANCE TO GLACIAL FORMS

The irregular surfaces produced by differential motion, especially when the forward part of a slide or combination of slides is crowded up, may give a gently pitted topography favoring the accumulation of water in the depressions. The lakelets thus formed are rarely permanent but may persist throughout the winter. These isolated surfaces suggest modest morainic topography. Sometimes whole hillsides are so cluttered with hummocks of slide masses that they resemble mild kame and kettle areas upon a tilted base. The scattered rock masses on hillsides, while usually more angular, bring to mind the erratics of glaciated country. A hillside from which much slide material has removed takes on a re-entrant character similar to that produced by the plucking action of ice and snow in a glacial cirque. Indeed as suggested by my colleague, Professor Brown, the separation of the slide from the parent mass resembles the bergschrund of a glacier. As bowlders from the resistant formations are frequently mingled in haphazard fashion with the clayey base, the heterogeneous character of glacial till is produced.

RESEMBLANCE TO DRAINAGE FORMS

Upcrowded masses, when of considerable extent, frequently resemble river terraces. These semblances may be hundreds of

feet in length, but rarely more than thirty feet in width. (Successive breaks in a slide mass often result in a series of small terraces or steps which may be likened to step faults.) In some cases the terraces are due to the position of a resistant rock ledge (Figs. 1 and 2). The overlying shales on this having been removed previously

Fig. 1.—Terrace at base of left-hand re-entrant as shown in next view. Slide material has accumulated irregularly on a ledge of the Saltsburg sandstone (in Lower Conemaugh), resulting in a general terrace form with lakelets of precarious life in the hollows.

either by slides or former river action, subsequent slides have spread over the top and flattened to rough conformation with the rock ledge.

Sometimes slide material will accumulate at the base of a slope in the form of a fan or cone, the accumulation probably being the result of a combination of the slide types. A hillside cut marking the source of at least some of the slide material usually leads to it. While these features are still fresh their origin can hardly be questioned. With the passage of time the slide gullies may become

true drainage lines, and the fans and cones become covered with vegetation. They would then be mistaken for forms of stream origin. There is little doubt that many of the so-called alluvial fans and cones in the area discussed have had this history. The later modification may entitle them to their present names. The delta-like products of the fluid slides would also originate such forms.

FIG. 2.—Two huge re-entrants meeting. These are the product of slides which have progressed to near the hilltop. Note the steepening effect produced by slides at their upper limit. The ultimate result, obviously, will be a reduction in the height and gradient of the hill. Slides are still active over the entire surface of the re-entrants; several terrace-like forms are discernible in their midst. The terrace marking the base of the re-entrants, though covered with irregularly placed slide material, has had its form determined by the Saltsburg sandstone which outcrops beneath.

MINOR TOPOGRAPHIC FORMS ASSOCIATED WITH SLIDES

"Hoodoos"[1] and ice pinnacles are frequently found associated with slide materials.

HOODOOS

These are usually abundant on slide slopes after heavy rains. Great numbers will sometimes stand out as distinct columns, but on the steeper slopes the columns with their caps frequently coalesce

[1] See article by Rolf A. Schroeder, *Journal of Geology*, Vol. XXVII, No. 6, pp. 480–81.

on one side with the slope. This form may be so numerous as to give the whole surface of such a slope a peculiar columnar structure. Both kinds of hoodoos are evanescent features.

ICE PINNACLES

These forms are apt to coincide with the melting of snows on steeply sloping fresh slide surfaces, though it does not appear that slope is always necessary. They are tapering columns of ice a few inches in length, coalesced toward their bases, the columns extending with considerable variation at right angles to the surface on which they rest. While the individual pinnacles tend to be straight, many are curved and hooked in curious fashions. They are of principal interest in connection with this paper in that they as well as other ice masses permit the ready transmission of light to the frozen ground beneath where it is absorbed as heat, resulting in a superficial thawing of the surface and a melting of the underside of the ice. No longer properly secured these ice masses, with any enmeshed mud, break off and slide down. This also encourages movement in the thawing muds beneath.

TOTALITY OF EFFECTS

GENERAL TOPOGRAPHIC EFFECT

Taken in the large the topography is little different from a typical area in maturity, though broad hillsides sometimes show huge re-entrants or hummocky surfaces with frequent small terraces. Outcrops of resistant rock frequently indicate their position by steeper slopes even when slide covered.

A number of relatively large discontinuous terraces mark old positions of the Monongahela and tributary streams. These stream terraces may have some association with slide movements. In fresh cuts evidences of stratification, while not infrequent, are less common than till-like coverings. It is tentatively suggested that since the lowering of the streams, movements within the terrace deposits and the addition of slides from the hills may account for the heterogeneous masses so often found.

Where old valleys of somewhat shallow depth are practically confined to shales, the slopes are more mature, as the sliding

continues unchecked by beds of resistant rock. As limestone and coal members are generally weak, the interfering rock is practically limited to the thick sandstone beds.

IMPORTANCE AS A BASE-LEVELING FACTOR

The importance of these slides as a base-leveling factor can hardly be overestimated. Widespread changes are observable as a result of a single season of activity. No other single agency produces comparable results except as associated with this factor. In this sense streams are of highest importance as by their removal of slide masses, a continuency of the movements is permitted.

INFLUENCE ON DRAINAGE

Gully-like forms and similar depressions due to slides are such common features of hillsides or at the edge of slide or stream terraces, that they furnish the readiest lines for drainage of nearby surface areas and for the ground water. It is very probable that most of the minor streams whose courses have been determined under present stratigraphic conditions have had these courses determined in some measure by such depressions.

SIMILARITY OF THE CONEMAUGH TO OTHER FORMATIONS

The Monongahela and Dunkard formations which were laid down following the Conemaugh, show a somewhat similar stratigraphic arrangement with shales of unstable character. Their outcrops, like the Conemaugh, lie in the Alleghany Plateau. Gently dipping northwest, with usually mature topography, slide conditions throughout their outcropping extent do not differ greatly from those of the Conemaugh, though the Dunkard shows some interesting differences.

ECONOMIC CONSIDERATIONS

While most of this territory is subject to surface modifications on account of slides, the damage within the city of Morgantown is less serious than might be inferred. This is due in large measure to the situation of most of the city on the several comparatively level terraces of the Monongahela River and tributaries. By utilizing the connecting slopes as well as some of the land rising

above the well-defined terraces, the city has avoided extending its territory excessively. The connecting slopes have caused little trouble in the business district. This is in part due to the fact that the terrace positions were largely determined by the resistant rock. The removal of slaked shales, grading, and the protective effect of building and paving operations have all helped in preventing serious trouble. In the outlying territory dwellings built on

FIG. 3.—Walls and steps pushed forward as a result of slide movements. The house in the foreground is in immediate danger. Note jagged edge of broken brick walk leading to house in the rear. As is frequently the case, the sliding masses have produced a terrace-like form, with the vegetation growing on its top but little disturbed. Many months were required to produce the foregoing result.

terrace slopes and on the upper hill slopes are sometimes endangered by slides, and precautions have to be taken to prevent their destruction. The most effective preventive of trouble is the exercise of foresight, the position a house is to occupy being considered with reference to this difficulty. Sometimes thick retaining walls are built at the time to insure safety. That such walls prove inefficient at times is shown by the accompanying figure. Some

lots plotted for building purposes are totally unfit for such use, a fact which usually becomes apparent before construction is started. In a few instances the grading of roads, or changes of drainage by fillings or other causes, has been charged with starting slides endangering structures. Such instances have usually resulted in lawsuits to determine the influence of such changes and also to place responsibility.

Fig. 4.—Slide partially blocking roadway. The entire face of the slope above the slide is bare to a height of about forty feet, the result of recent slides.

The greatest source of trouble comes from the roads leading out of the city. As the terraces on which the city is built are fragmentary, roads cannot follow them for great distances. If outlying districts are to have communication with the city, the building of roads along or at the base of hillsides is unavoidable. While poor engineering judgment is sometimes shown in locating the roads, with the best of skill the ultimate damage can only be lessened. The present roads, including several regraded and paved within the last few years, have suffered repeatedly, sometimes by block-

ing caused by upslope slides, sometimes by caving, the result of downslope slides. The most obvious remedy for the former is to reduce the slope by cutting away on the uphill side, and to produce the same result by filling in on the lower side. On the new slopes so made the growth of vegetation should be encouraged. It might prove practicable in extreme cases to prevent saturation of the trouble-making shale by well-planned drainage. Heavy retaining

Fig. 5.—Slides have undermined the brick-paved road at this point. The line of dirt through the center of the road fills a crack and reduces the gradient between the sides of the offset. At the far end marked by the position of the man, half the road has dropped to such an extent as to require blocking off.

walls should be successful in some instances. These remedies may be considered applicable only in extreme cases, or with such portions of the road where the trouble is due to the cut made in grading. The total avoidance of damage would mean a cost in preventive arrangements greater than the total of prospective damage.

Electric railroads are subject to the same conditions as the highways. The steam railroads in the immediate vicinity of

Morgantown are built on natural or artificial terraces cut in the Buffalo sandstone, one of the lower Conemaugh members. As the lower part of this massive sandstone forms the river bottom, the railroads here are free from undermining, but subject, especially when following close to the hillsides, to occasional slides from above. The removal of these causes immediate expense as well as delays. By the liberal use of watchmen in deep cuts and frequent "slow orders" in times of excessive rainfall, few wrecks are fortunately chargeable to this cause. A better understanding of the shales would result in relocating parts of the tracks.

As slides are much more frequent in seasons of abundant rainfall than in seasons of light fall, the damage to roads and various structures and loss by delays increases or decreases accordingly. The past year (1919) was one of abnormal rainfall, roughly about one-fourth greater than the average, the fall months having more than their share of the excess; consequently the year and especially the latter months proved unusually costly. The generally slow movement and small volume of the individual slides have meant that private parties have rarely suffered disastrous losses. While no total can be estimated for the average yearly loss to the community, there is no question that this would amount to a big sum.

An indirect loss, though much more than all others in the aggregate, is that caused by the withdrawal of farmland from cultivation. Slopes not too steep for the plow under light rainfall conditions, when charged with water may start movement which a vegetative covering would have checked. Such slopes are best reserved for grazing or forest growth. This is well understood by farmers, and very little land except flood-plains, terraces, and hilltops is ever plowed. The effect of the Conemaugh in limiting cultivation is well indicated by the fact that other and especially older formations in West Virginia permit cultivation on much steeper slopes than allowable in the Conemaugh, without sliding.

The shale soils, where they can be used, are generally productive. Especially is this true when they have a pronounced lime content, either native or infiltered from higher beds.

The frequent undermining of sidewalks along the roads on the edge of the city would seem to furnish a fruitful source for accident,

likewise the obstruction or falling in of roads. The frequency, however, is itself the safeguard, the population having become educated to the danger, and consequently taking proper caution. The injuries from such causes have been few.

It may be noted that slides have never been of sufficient extent to interfere with the use of the Monongahela River since rendered navigable.

The only direct economic benefit from the slides lies in the fact that brick, ordinarily made by grinding the shale, can be made of almost equally good quality and less expense for handling from the slide material. When work in the shale is interfered with by slides, the material in these is used.

The shales worked at present near Morgantown are near the base of the Conemaugh, though shales higher in the formation are frequently used elsewhere. Formerly brick was made from river-terrace clays, these clays resulting doubtless from the assortment of shale muds reaching the rivers as slides and from direct stream action.

A REPLACEMENT OF WOOD BY DOLOMITE

S. F. ADAMS
Stanford University

A score or more minerals are known to have replaced wood. Cases of most of these types of replacement were recorded by J. R. Blum[1] during the years 1847–79. Since 1879 there have been few additions to the list of wood-replacing minerals as given by Blum. To my knowledge, replacement by dolomite has not before been mentioned. For this reason, the accompanying account has been made as complete as possible.

In the known replacements of wood chalcedony is undoubtedly the most universal petrifying mineral. Fine examples of this kind of replacement are found in the petrified forests of Arizona, where very large tree trunks have been completely agatized.[2] Petrifactions of this type come from localities in Colorado, Utah, California, and from the Yellowstone Park. I have at hand an unlabeled specimen of petrified wood which is thought to come from Arizona, in which the wood is largely replaced by quartz. A thin section of this specimen shows anhedral quartz crystals which include sometimes a dozen well-outlined wood cells. The general character of the quartz is similar to that to be described on a later page. Wood opal replacing entire tree trunks is found in Hungary; nor is it uncommon in this and other countries. Precious opal, usually as a late development after common wood opal, is known to come from Australia and from a deposit in Nevada, where the opal is being recovered for commercial purposes. Blum mentions opalized wood with an incrustation of hyalite.

Replacements by calcite and aragonite have been recognized in many places. The strong crystallization of these two minerals

[1] J. R. Blum, *Pseudomorphosen des Mineralreichs*, Nachträge, 1, 2, 3, 4.

[2] G. P. Merrill, "The Fossil Forest of Arizona," *Am. Mus. Jour.*, Vol. XIII, pp. 311–16.

usually obliterates the cell structure of the wood. An interesting case in which the wood tissue is well preserved by calcite has recently been described by C. W. Greenland.[1] Fragments of wood and plant remains petrified by pyrite, and marcasite are recorded from carbonaceous formations of many districts. Blum describes replacements of wood by barite, from the Lias chalk beds of central Germany; by cinnabar, from Bavaria; by fluorite, from Saxony; by sulphur, from Italy; and by malachite and azurite, from the Urals and West Africa. The same author also records replacements of wood or plant remains by gypsum, phosphorite,[2] hematite, limonite, siderite, sphalerite, galena, chalcopyrite, and chalcocite. He mentions a case in which wood tissue is well preserved by a kaolin-like substance most closely resembling halloysite. Blum also discusses replacements of wood, from near Moutiers in the French Alps, by a mineral closely resembling talc, and compares this mineral with some pyrophyllite from the Thuringen district in Germany. The pyrophyllite, however, is not described as replacing wood. Grabau[3] mentions chlorite as replacing plant remains.

In an article on the "Red Bed" type of copper ores, Rogers[4] lists as occurring in petrified wood: hematite, pyrite, bornite, chalcocite, chalcopyrite, covellite, melaconite, limonite, malachite, azurite, and quartz. Of these, only hematite and pyrite are considered as directly replacing wood.

The dolomitized wood herein described belongs to the mineral collections of Professor A. F. Rogers, of Stanford University, to whom I am indebted for the privilege of describing it as well as for suggestions as to the description itself. The specimen was found in 1916 in the Midway Oil Field, Kern County, California, by C. R. Swartz. It comes from what is locally known as the McKittrick formation, which may include sediments of upper Miocene, Pliocene, and Pleistocene age.[5]

[1] C. W. Greenland, *Econ. Geol.*, Vol. XIII, pp. 116–19.

[2] Probably impure collophane.

[3] A. W. Grabau, *Principles of Stratigraphy*. A. G. Seiler & Co., 1913.

[4] A. F. Rogers, *Econ. Geol.*, Vol. XI, pp. 366–80.

[5] Arnold and Johnson, *U.S.G.S. Bull. 406*.

The hand specimen measures four by three by two inches (Fig. 1). Worn and rounded corners indicate that it is float, for which reason the horizon from which it came cannot be more definitely established. The specimen is of two distinct colors, a buff outer part which may correspond to sapwood, and a dark-gray inner part which may have been heartwood. The former is dolomite, the latter silica. Qualitative analysis of the dolomite gave roughly half as much magnesium as calcium and an appreciable, though not large, amount of iron. The general buff color throughout the dolomite is due as much to the oxidation of this iron as to organic matter. Both Professor D. H. Campbell and Professor Leroy Abrams, of Stanford University, have determined the wood as that of gymnosperm and almost assuredly coniferous. Due to the imperfect preservation of fiber, further identification was not made.

FIG. 1.—Wood replaced by dolomite. Gray part is compact dolomite showing radial lines and small black siliceous dots, which may represent location of resin ducts. In center of specimen is coarser dolomite in rhombs and compound groups. Black portion, showing annual rings, is quartz. (Slightly reduced.)

In the center of the specimen is a spot of darker brown color containing rather coarse dolomite crystals. In this place a feature which has been described by E. T. Wherry[1] (in an account of a petrifaction by calcite from Yellowstone National Park) is rather prominent, e.g., the individual or compound convex-bordered crystals in a siliceous matrix. On either side of the central darker area is the buff mass of dolomite replacing the outer portion of the

[1] E. T. Wherry, *Proc. U.S. Nat. Museum*, Vol. LIII, pp. 227–30.

specimen. The most noticeable feature in this part is the parallel radial lines of buff dolomite. Adjoining lines usually are separated by fine brownish black silica.

Small dolomite crystals grouped radially about a center of silica also can be seen in this part of the specimen. These groups are made prominent in the hand specimen by the black silica cores. They occur with apparent regularity throughout the dolomite, and

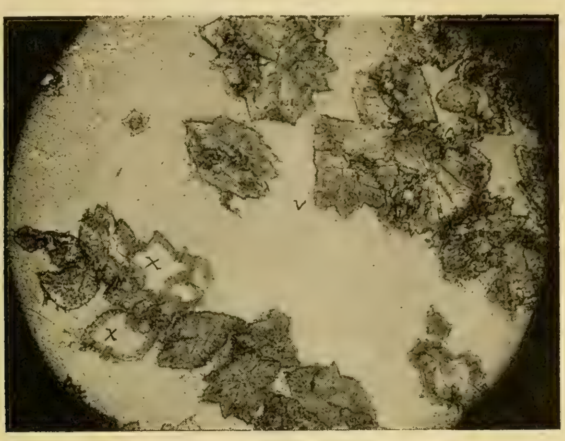

Fig. 2.—Thin section showing compound dolomite crystals in siliceous matrix. Replacement of dolomite by silica is illustrated around places marked "*x*." White central part (at "*x*") is a hole in the slide where the dolomite has pitted out. The fringe around the hole is silica, surrounded by the darker organic matter excluded by the dolomite during growth. This same effect can be seen around most of the rhombs. This section also shows second generation dolomite developing along the edges of the older rhombs as at "*v*." $\times 9\frac{1}{2}$.

it was at first suggested by Professor Abrams that they might mark the location of resin ducts. This seems doubtful unless the outer part of the specimen is a petrifaction of bark. However, recognition of wood structure throughout the dolomite is at best largely a guess.

Annual rings are not well preserved in the dolomite. In the dark-gray siliceous part of the specimen, however, annual rings are prominent. They are marked by the gradual darkening of color from spring growth to winter. In one or two places there are

cavities with inwardly projecting quartz crystals. Small euhedral quartz crystals have developed on the outside of the siliceous portion of the material.

Under the microscope the individual dolomite crystals are first to attract attention (Fig. 2). The well-developed rhombs usually average about one millimeter on the long diagonal. The dominant form is the unit rhombohedron $r(10\bar{1}1)$, sometimes modified by

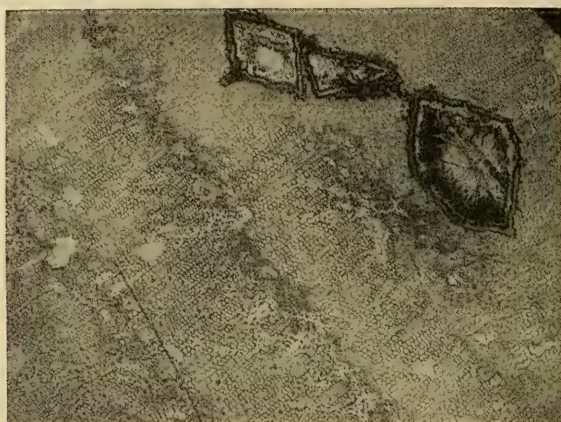

FIG. 3.—Thin section of corroded dolomite rhomb in quartz ground-mass. Also showing patchy retention of cell outlines, especially along annual rings. Notice apparent distortion of cells bordering the larger dolomite rhomb. $\times 21\frac{3}{4}$.

$e(01\bar{1}2)$. These crystals neither include nor preserve any cell outlines. A dark-brown rim around the edges indicates that they have excluded the woody material. Replacement of the crystals along borders by finely crystalline silica leaves a corroded dolomite core surrounded at a little distance by a brown organic halo, as the development of the silica does not affect the position of the organic matter (Fig. 3). In a few cases, surrounding groups of cells seem to have been squeezed by the growth of the rhombs. Cells are usually misshapen near the annual rings. However, one or two occurrences can be seen in which cells, bordering dolomite crystals which lie entirely within the customarily well-developed spring growth, are distorted as if by pressure from the crystal (Fig. 4). This is an indication of the formation of the

dolomite before the surrounding silification. In general, cell outlines are not evident near the borders of dolomite rhombs. Had the dolomite been a replacement of silica, one would expect to find the cell outlines in the silica as well preserved in the immediate neighborhood of the rhombs as elsewhere. The exclusion of woody material is also evidence of the early crystallization of this dolomite.

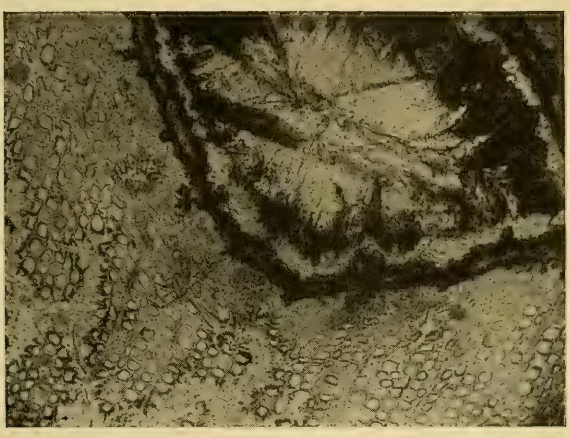

FIG. 4.—High power view of rhomb in Figure 3, showing dolomite core, organic rim, and silica fringe separating the two. Also shows distorted cells. $\times 76\frac{5}{8}$.

In the main mass of buff dolomite the crystals are slightly smaller than the rhombs just mentioned, and they rarely show crystal outlines. With magnification the thin section appears to be a compact mass of rather even fine-grained crystals, usually about twice as long as wide. Many crystals appear to be twinned. No polysynthetic twinning was noticed either in the thin section or in fragments. An approach to cyclic twinning is occasionally seen, but commonly the apparent twinning is of a simple contact nature. However, the presence of twinned crystals was not proved.

The dolomite crystals are sometimes arranged side by side in long rows; opposite them is a similar row; and along the center where the rows touch are two imperfect chains of distorted cell outlines. The rows are always arranged radially with respect

to the replaced wood as a whole. Although these "chains of cells" include varied sizes and odd shapes, it is safe to say that they are a relic of the original vegetable fiber. The size of the cells in these chains varies from 0.02 mm. to 0.07 mm. in diameter and averages 0.04 mm., which is a range in size and an average also true of cell outlines well preserved by silica. Occasional cells are replaced by individual dolomite crystals which do not extend beyond the cell walls, and still other cells show evidence of secondary enlargement of dolomite, proceeding outward from the cell as center. Cell outlines in dolomite are not often retained except in or near the cell chains. The parallel row arrangement is repeated throughout much of some of the thin sections. It is this arrangement which causes the radial lines of buff and black as seen in the hand specimen. The fine black lines are composed of a late silica which develops most readily between the abutting ends of the dolomite crystals. An explanation for this phenomenon which seems tenable is that the dolomite started crystallization simultaneously along somewhat widely spaced radial lines; that in the first crystallization some of the cell outlines were preserved; but that in the subsequent growth wood structure was largely obliterated. Judging from the secondary enlargement of dolomite with a cell as a center, the initial crystallization occurred within the cell, in some cases at least.

Often the dolomite crystals are grouped radially with a small center of finely crystalline silica of the same late type as just mentioned. The silica, of course, is a development subsequent to the radial growth of the dolomite. The siliceous cores of these groups are seen as fine black dots in the hand specimen. Extinction in sequence often occurs in the radially grouped dolomite, and when combined with simultaneous extinction in opposite sectors, gives the group a rough spherulitic appearance.

Thin sections of what has been called the heartwood show the best retention of cell structure and annular rings. For the most part, the replacing mineral is quartz.[1] Crystals are usually

[1] The exact relations of quartz, chalcedony, fibrous, and other forms of silica have not been settled. In this article the identification of quartz as such is made easy by its occasional euhedral form. The chalcedony to be mentioned later was so called on account of its lesser refractive index than quartz and negative elongation.

anhedral and of a fairly uniform size in any one part of the thin section, although the average size for the different parts of the specimen may vary from very small to a maximum width of about 0.2 mm. In general, it is the rule for one quartz crystal to contain several wood-cell outlines. As before stated the average diameter of cells is 0.4 mm., with a range of from 0.02 mm. to 0.07 mm. In longitudinal sections the quartz is usually elongated in the direction of the wood fiber, showing that the growth of crystals has been influenced by cell structure. Distinct crystal outlines with an occasional hexagonal cross-section are noticeable in several places throughout the anhedral quartz. They are better-developed individuals belonging to the same silification. As may be seen in one of the accompanying photographs (Fig. 3), retention of cell structure is patchy. The best-developed quartz crystals occur on the borders of those places in which no cell structure is evident. They give the appearance of having grown into an open space, or at least into a decayed spot, where there was nothing to resist their assuming idiomorphic form. At their roots these crystals also inclose cell outlines.

Secondary enlargement of the euhedral and subhedral crystals is seen in several places. A rough radial grouping occurs in some of the quartz. Extinction in sequence often gives these groups the same coarsely spherulitic appearance as in the dolomite. Wavy extinction is common in many crystals. In one thin section cell outlines are well preserved by another form of silica. This silica is very fine grained, fibrous, often spherulitic, with very weak double refraction, about the same index of refraction as quartz, and of negative elongation.

Late silica and dolomite are found in veinlets and cavities. In several small veinlets which cut both siliceous ground-mass and early dolomite crystals, banding by alternating quartz and dolomite occurs. Dolomite also is found in patches throughout the quartz replacement of heartwood. In cavities it is often in the center as a filling around projecting euhedral quartz crystals. A very prominent occurrence of this late dolomite is as an enlargement, although not in crystallographic orientation, of the older rhombs and dolomite crystals.

The later silification develops with this dolomite as a replacement of the previously formed quartz and dolomite as a cavity and vein filling, and as an incrustation. That it actually replaces the earlier quartz is not certain, but its replacement of dolomite is manifest in the corroded rhombs separated from their excluded organic halo by silica. Chalcedony and quartz occur in this silification. Quartz predominates. It occurs in subhedral crystals in veinlets, presenting a microscopic comb structure, or as cavity filling, in which case it has developed from the walls inwardly as in a geode. In both of these cases it often shows zonal lines. It replaces the dolomite around the borders, and, especially in the case of the compound dolomite groups, it begins replacing in the center of the group as well as along the edges. The development between parallel rows of dolomite crystals has already been mentioned. The chalcedony and fibrous silica are found in the centers of filled cavities, in veinlets, and as a replacement of dolomite.

Another very interesting late development is that of minute patches of an opaque gray metallic mineral, taken to be hematite, but in too minute amounts to test. This appears in a polished surface in veinlets and patches and in one case in a small rhomb as if it were a pseudomorph after dolomite.

In conclusion: dolomite seems to be the earliest replacing mineral. The small area of large-sized rhombs is taken to be the result of replacement in a partially rotten or injured spot in the wood. The outer part of the specimen was replaced by a finer-grained dolomite, but without retention of much of the cell structure. The curious arrangement of crystals in rows points to initial crystallization along radial channels. What furnished these channels is not clear. The distance between rows is greater than the spaces between medullary rays. Also, the channels have longitudinal extent, which leads to the possible hypothesis that they were caused by closely spaced radial cracks.

From the general character of the petrification it appears that crystallization took place rather slowly along certain lines, later spreading throughout the wood and destroying most of the cell outlines. For some reason these solutions gave out before complete dolomitization, for the inner part of the specimen shows no evidence

of having been attacked by dolomite. Blum describes a petrifaction by opal in which the outer part is opal, whereas the core is unaltered wood, showing that replacement progressed from the outside toward the center. It may be that in the case in hand petrifaction occurred while at least a complete cross-sectional fragment of the wood was intact, and that dolomitization started from the outside and developed inwardly. The solutions containing the carbonate then gave place to others with silicic acid which permeated the heartwood and caused its silification. Cavity and crack fillings, and rearrangements, followed at some time later.

A DISCUSSION OF "NOTES ON PRINCIPLES OF OIL ACCUMULATION" BY A. W. McCOY[1]

CHESTER W. WASHBURNE
New York City

In many ways this is one of the most interesting articles on the accumulation of oil that has appeared. I have long held many of the conclusions reached by Mr. McCoy in this paper, and it is a great pleasure to find these ideas corroborated by his experiments, which have been cleverly conceived and executed. It is unnecessary to reiterate the good points of the paper. It will be more useful to call attention to some of the more doubtful conclusions, in the hope that further study by McCoy and others may clarify these points.

Origin of oil.—The first experiment shows that liquid oil may be formed by the deformation of oil shale which previous to deformation contained only solid organic materials. McCoy states that "no appreciable amount of heat was developed." It seems to me impossible to deform the steel cylinders and to crush and shear the inclosed shale without causing an appreciable increase in temperature. If the experiments had been carried out in cylinders under water and if the temperature of the latter had been measured after the completion of the experiment, I believe McCoy would have found that there had been a material loss of energy in the form of heat. Shale is notoriously a poor conductor of heat. Therefore there must be a material rise in temperature along every plane of shear. As stated by McCoy, differential movement in shales probably is an important cause of the alteration of solid organic matter into oils. However, it is probably heat rather than pressure which causes this alteration. Heat is a common cause of the dissociation of various molecules. Pressure

[1] *Jour. Geol.*, XXVII (1919), 252–62.

never has been known to split a molecule of any kind; nor has mere "mechanical energy." It will require an entirely new concept of the molecule to assume that a mechanical shear can cut a molecule. Only vibratory forces, like heat, light, electricity, and subatomic radiations are now thought to be capable of penetrating molecules. The mechanical energy of McCoy's experiment must have been transformed into one of these other forms of energy before it could split the molecules of organic solids.

The formation of oil is a process which results in a great increase in the volume of the original solid material, which is converted into new solids, liquids, and gases. Pressure therefore is a condition which might be expected to retard rather than accelerate the process. In fact, the distillation experiments by Engler have shown that pressure retards the thermal dissociation of fats. The principal effect of pressure in this connection is to cause an inward shift in the point of splitting within the solid organic molecules. High pressure causes the splitting to take place farther from the surface of the molecules, resulting in the formation of less gas and coke and of more of the intermediate or liquid products. The same phenomenon also appears to rule the operation of the high-pressure stills of cracking plants, decreasing the amount of gas and residue in the product, and increasing the amount of gasoline, and under certain conditions increasing the yield of kerosene. Therefore high pressure in the rocks probably is a useful and essential condition for the formation of oil. It is not, however, the main cause of the formation of oil. There is nothing in this experiment to indicate that heat is not the principal agent that splits solid organic molecules into gases, oils, and carbon-rich residues such as asphalt.

A slight increase in temperature may be enough to initiate the process, after which the release of the endothermic heat of formation evolved by the splitting of the first molecules would increase the temperature of adjacent molecules. Thus, when once initiated by any cause, the process of thermal dissociation of solid matter into oil, gas, and black residue would tend to perpetuate itself and to increase, like spontaneous combustion, as long as there was an abundant supply of endothermic organic matter present.

There is reason to doubt that the known types of oil shale had anything to do with the formation of oil. Many of these shales, as in Scotland, New Brunswick, and New South Wales, have undergone such severe deformation that if their contents were capable of being converted into crude oil by such means, it is hard to understand why they have not all been completely converted. Yet in these fields there is no indication that any of the oil-shale has been altered into crude oil. Reagents will not extract more than a trace of oil from them. The oils obtained from them by distillation consist largely of unsaturated hydrocarbons which could not be converted into the better types of natural crude oils except by hydrogenation. Hydrogenation seems impossible in nature. Moreover, the collection of numerous analysis by Hoefer shows that the oil shales of various ages exhibit an increasing ratio of carbon to hydrogen in the samples from older rocks, indicating that the course of metamorphism of oil shales is very similar to that of coal, and that the organic matter in these shales tends to become harder and richer in carbon with the passage of time. There is some suggestion that the oil shales of Colorado and Utah and the Cannel coals of Kentucky will be found to be of this same general type. The substances in shale which have been converted into crude oils very likely are of a nature somewhat different from the organic matter in the types of oil shales that have been studied. The nature of this difference is a problem for future investigation. This point may be determined by distilling unaltered marine oil shales, preferably of the Late Tertiary, and by studying the decomposition of the fats and waxes of modern organisms.

Oil migration in wet sand.—Mr. McCoy's third experiment shows rather clearly that under ordinary temperatures oil will not migrate away from the larger pores in a sand under the influence of gravity aided by rather strong circulation of water. The capillary forces involved are strong enough to hold the oil in the larger pores against the influence of gravity and water circulation.

It would be very interesting to have this experiment repeated under the temperatures that prevail at depths of a few miles, where capillary forces are greatly reduced. The viscosity of the oil also is reduced. A useful point has been established by

McCoy in showing that under common surface temperatures a comparatively vigorous circulation of water will not remove oil from the larger pores of the sand. It does not follow, however, that water circulation could not do this at depths of two or three miles, which does not exceed the probable thickness of strata that formerly covered many oil sands. Further experiments under appropriate higher temperatures are needed to show that gravity alone could not produce anticlinal accumulation in sands buried under a few miles of rock.

Anticlinal accumulation.—Mr. McCoy appears to believe that the lateral migration of oil in sands is of minor importance. He believes that the anticlinal accumulation, which characterizes most fields, is due primarily to migration along nearly vertical shale joints, which are most abundant theoretically on the crests and limbs of anticlines.

There is an asymmetrical distribution of oil in the Cushing and Yale fields, Oklahoma, and in other places where the basin-ward limbs carry the most oil, and carry oil to the lowest structural elevations. This indicates that lateral migration up the slope of sandbeds is an important element in anticlinal accumulation. On the other hand, the frequent distribution of oil in various sands, one above the other, and all above the probable source, as in the Wyoming domes, indicates the importance of joints across the shales. The relation to faults of the principal fields in Kentucky and northern Louisiana bears similar testimony.

The accumulation of oil in the sand of the Ranger field, which is "dry" outside of the producing territory, also suggests the inadequacy of lateral migration in the sands. The occurrence of oil in fractured chert on top of the Santa Maria anticline in California must have been due wholly to migration along nearly vertical crevices, since it would be impossible for oil to move laterally through the hard, dense, unfissured chert on the lower parts of the anticline. Wells drilled on the flanks of this anticline showed neither oil nor water when they passed through the chert horizon.

In spite of these interesting experiments it seems that the time has not yet come to abandon wholly our previous ideas that an

important part of anticlinal accumulation is due to migration up the slope of the sand. The experiments are important in showing the difficulty or impossibility of such migration under the low temperatures of very shallow depths. The experiments by McCoy show that we should give more thought to the importance of anticlinal crevices in shale.

REPLY TO DISCUSSION BY C. W. WASHBURNE ON "NOTES ON PRINCIPLES OF OIL ACCUMULATION"

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In reply to Mr. Washburne's discussion of this paper, each of his main points will be answered briefly in the following paragraphs.

The first criticism offered is that as to the origin of liquid petroleum from solid hydrocarbon waxes (commonly called kerogen) in the shale. The original paper states that "no appreciable amount of heat was developed," implying that the amount of heat developed was in no way comparable to the necessary distillation temperature for those hydrocarbons. The heat developed was not great enough to melt a thin coat of paraffin which had been placed around the bulging zone of the cylinders.

Moreover, the paper does not state that pressure was the direct cause for this change, but definitely says that pressure alone can cause no change in the material. It suggests that this change can take place in regions of differential movement, and that such zones are the only areas where liquid oil is likely to be made. Field observations indicate that such a condition exists, but a discussion of the point would necessarily be too long for this short statement. Pressure and release of pressure are essential for differential movement. The latter action is probably the real cause for any chemical change, whether resulting directly from developed heat or otherwise.

Mr. Washburne's suggestion that the chemical action of forming liquid petroleum from solid waxes is an exothermic one, and when once started will generate heat to carry on the action, neither agrees with the work of Engler and Hoefer, nor with the evidence gathered by the author from laboratory distillations. Before this

point could be considered seriously it would be necessary for Mr. Washburne to show the chemical equations of the action, the amount of heat absorbed or given out by each combination, and the resulting heat from the summation.

From the literature available, the author has been unable to secure enough detail on the geology of the Scottish oil shales to determine to what extent the shales have been altered, and how tests for liquid oil have been carried out in relation to such places. It is a well-known fact, however, that there are a few veins of gilsonite and other heavy hydrocarbons in joints or small fault planes of the Colorado-Utah oil shales, although they have not been altered by any widespread movement. These shales, as well as those of Scotland, are most probably non-marine in origin and differ somewhat from the marine type of bituminous shales which furnish petroleum.

The suggestion that the experiments should be carried out under pressures and temperatures prevalent for depths of several miles is good but unnecessary. At any given depth the temperature could be estimated, so that with temperature and the size of the openings known, it is merely a physical problem to determine the action. Pressure has such a small effect on surface tension that it may be neglected. Moreover, the majority of the oil sands in the Mid-Continent Field have never been buried more than five or six thousand feet and the actions at such depths are similar to those described in the experiments.

Mr. Washburne states that the asymmetrical distribution of oil in the Cushing and Yale fields indicates that lateral migration up the slope of sand beds is an important element in anticlinal accumulation. The author disagrees with this statement, as it is only a popular notion among oil geologists which has never had any substantial, scientific backing. On the other hand, the arrangement of the oil in these pools has a marked relation to the stress lines of the region and can be explained satisfactorily by this method as in the other pools of the mid-continent. Such an explanation would necessarily be long and does not directly refer to the subject of the original paper.

To say that the time has not yet come to abandon previous ideas concerning oil migration up the slope of a sand is only helping to cover a weak link in the anticlinal theory, and passing the responsibility of correcting questionable points before precedent has established a dangerous stone in the progress of the new science. Oil geology is now undergoing a crisis in its history, so the time is ripe for each follower in the science to face the facts squarely and to strive with an unbiased mind to reach the correct solution of oil accumulation phenomena. One of the world's greatest industries demands, by its expenditures of millions, that those offering scientific interpretation endeavor to gain the clearest and most logical principles based upon the maximum of details.

The discussion of this article has been most welcome.

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Among articles to appear in early numbers of the *Journal of Geology* are the following:

Diastrophism and the Formative Processes. XII. The Physical States of the Planetary Nuclei during their Formative Stages. XIII. The Planetesimals and their Infall. By T. C. Chamberlin.

The Heart Mountain Overthurst. By D. F. Hewett.

Notes on the Mechanics of Geologic Structures. By Warren J. Mead.

Geologic Reconnaissance of the Southern Part of the Taos Range, New Mexico. By John W. Gruner.

Preliminary Description of a New Suborder of Phytosaurian Reptiles with a Description of a New Species of Phytosaurus. By E. C. Case.

Summaries of Pre-Cambrian Literature of North America. By Edward Steidtmann.

A Test of the Feldspar Method for the Determination of the Origin of Metamorphic Rocks. By C. G. Carlson.

A Pleistocene Peneplain in the Coastal Plain. By H. F. Cleland.

The Mineralography of the Feldspars. By H. L. Alling. To be published as a supplement to the Journal of Geology.

VOLUME XXVIII NUMBER 5

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RECENT STUDIES OF THE UPPER CRETACEOUS OF TENNESSEE[1]

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After an interruption of two years, due to the recent war, the Tennessee Geological Survey has taken up again the study of the Upper Cretaceous series of West Tennessee, an investigation inaugurated in 1915 under the late Dr. A. H. Purdue. The field studies, collections, and surveys necessary for this investigation are now more than three-fourths complete, and it is the purpose of this short paper to give an abstract of the general areal and stratigraphic geology of the region, to touch lightly on the large well-preserved Ripley fauna discovered in the southern part of the state in 1915, and to announce the discovery in 1919 of a large and important Ripley flora in the northern part of the state.

HISTORICAL SKETCH

The first adequate map and separation of the Upper Cretaceous series of Tennessee into formational units was published by Safford[2] in 1869. Troost and others had previously written a little of the Cretaceous of this state but had not definitely described the formations. Safford's work was based on faunal and lithologic studies

[1] Published by the permission of Wilbur A. Nelson, State Geologist of Tennessee.

[2] J. M. Safford, *Geology of Tennessee*, Nashville, 1869, map and pp. 410–21.

and has been little changed even to the present day. In 1906 Glenn[1] published a map and gave a good, serviceable, and important account of the Upper Cretaceous of Tennessee along with his report on the geology and water resources of Tennessee and Kentucky west of the Tennessee River and of an adjacent area in Illinois. Nelson gave a short discussion of the Upper Cretaceous in connection with his studies of the clay deposits of West Tennessee[2] in 1911. The occurrence of the Tuscaloosa formation in Tennessee was shown by the work of Miser[3] on the Waynesboro Quadrangle in 1913. The McNairy sand member of the Ripley was differentiated by Stephenson[4] in 1914. In this same publication the Tennessee Upper Cretaceous deposits were correlated with beds of the same age in eastern United States. In 1916 Berry[5] published an account of about twenty-four species of fossil plants collected from the Ripley and Eutaw of McNairy and Hardin counties. In 1916 and 1917 the writer[6] published several short papers on the discovery of and some observations on a large Ripley fauna of McNairy County and a single article on the occurrence of the Tuscaloosa formation as far north as Kentucky. In 1919 Schroeder[7] gave a very brief outline of the Cretaceous in connection with his report on the Ball Clays of West Tennessee. In the latter part of 1919 Berry[8] published a very comprehensive discussion of the Upper Cretaceous Geology of Tennessee in his monograph on the *Upper Cretaceous Floras of the Eastern Gulf Region.*

During 1915 and 1916 the writer mapped in detail the areal distribution of the Upper Cretaceous formations in McNairy, Decatur, and Chester counties, and in 1919 this work was carried

[1] L. C. Glenn, *U.S.G.S. Water Supply Paper No. 164* (1906).

[2] Wilbur A. Nelson, *Tennessee Geological Survey Bull. No. 5*, Nashville, 1911.

[3] H. D. Miser, *Resources of Tennessee*, Nashville, Vol. IV, No. 3 (1913), p. 107.

[4] L. W. Stephenson, *U.S.G.S. Prof. Paper 81* (1914).

[5] E. W. Berry, *Torr. Bot. Club Bull. 43*, pp. 283–304, Pl. 16 (1916).

[6] Bruce Wade, *Proc. Acad. Nat. Sci.* (Phila., 1916), pp. 455–71, Pls. XXIII, XXIV; *Am. Jour. Sci.*, Vol. XLIII (1917), p. 293, Figs. 1, 2; *Proc. Acad. Nat. Sci.* (Phila., 1917), pp. 280–304, Pls. XVII, XVIII, XIX; *Johns Hopkins Univ. Cir.* (March, 1917), pp. 73–106.

[7] Rolf A. Schroeder, *Resources of Tennessee*, Vol. IX, No. 2 (1919).

[8] E. W. Berry, *U.S.G.S. Prof. Paper 112* (1919).

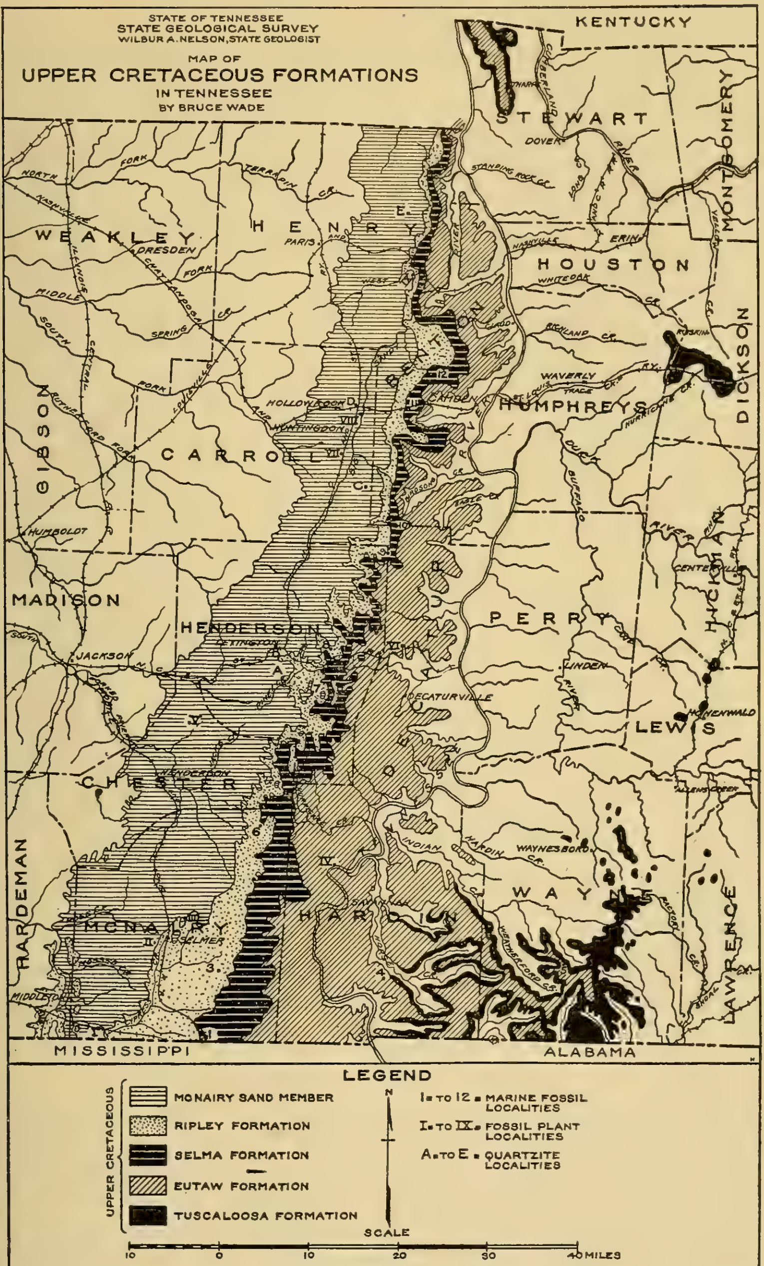

STATE OF TENNESSEE
STATE GEOLOGICAL SURVEY
WILBUR A. NELSON, STATE GEOLOGIST
MAP OF
UPPER CRETACEOUS FORMATIONS
IN TENNESSEE
BY BRUCE WADE
KENTUCKY
STEWART
MONTGOMERY
WEAKLEY
HENRY
HOUSTON
BENTON
HUMPHREYS
DICKSON
GIBSON
CARROLL
MADISON
HENDERSON
PERRY
HICKMAN
DECATUR
LEWIS
CHESTER
HARDEMAN
MCNAIRY
HARDIN
WAYNE
LAWRENCE
MISSISSIPPI
ALABAMA
LEGEND
UPPER CRETACEOUS
MCNAIRY SAND MEMBER
RIPLEY FORMATION
SELMA FORMATION
EUTAW FORMATION
TUSCALOOSA FORMATION
1 TO 12 = MARINE FOSSIL LOCALITIES
I TO IX = FOSSIL PLANT LOCALITIES
A TO E = QUARTZITE LOCALITIES
SCALE
10 0 10 20 30 40 MILES

FIG. 1

northward, where it was completed in Henderson and Carroll counties and in a portion of Henry County. In 1920 or the immediate future the Tennessee Geological Survey plans to complete Henry, Benton, and Hardin counties and map the outliers of Cretaceous gravels on the uplands of Stewart, Houston, Humphreys, and Dickson counties. With the field work of all these counties completed information will be in hand for a complete report on the Upper Cretaceous of Tennessee.

GENERAL GEOLOGICAL RELATIONS

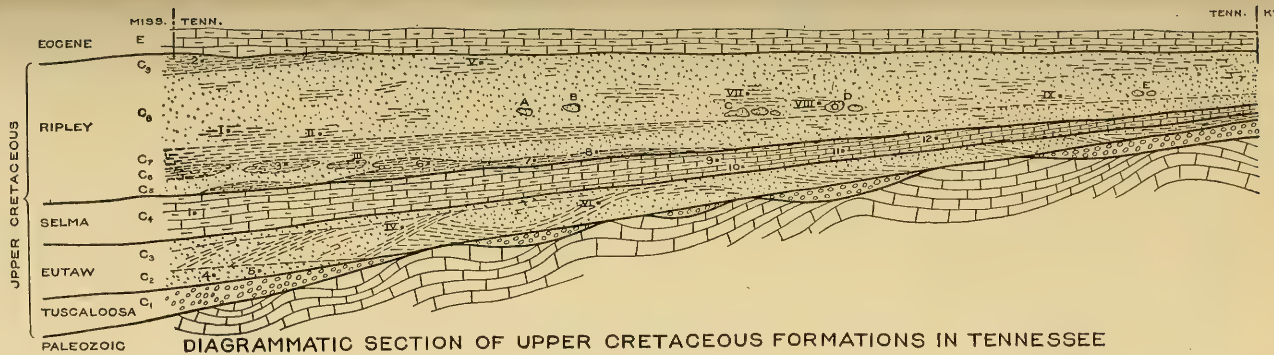
The Upper Cretaceous deposits of Tennessee outcrop in a wedge-shaped area which crosses the state in a nearly north and south direction, and lies largely west of the Tennessee River in the west-central part of the state (Fig. 1). This area is about sixty-seven miles wide along the southern boundary of the state, but narrows to the northward until at the Kentucky line it is only about fifteen miles in width. Along the southern border in Wayne, Hardin, McNairy, and Hardman counties these deposits have been segregated into the following lithologic units:

Ripley formation	Owl Creek horizon or member McNairy sand member Ferruginous clay horizon or member Coon Creek horizon or member
Selma chalk or formation	
Eutaw formation	Coffee sand and clay member Tombigbee sand member
Tuscaloosa formation	

In the northern part of the state these sediments diminish very greatly in thickness. The four major formational divisions may be recognized but the members or subformations lose their identity (Fig. 2).

THE TUSCALOOSA FORMATION

The Tuscaloosa formation is the basal member of the Upper Cretaceous series in the eastern gulf region of the Mississippi embayment. In western Alabama and eastern Mississippi this formation consists of irregularly bedded sands, clays, and gravels having an estimated total thickness of 1,000 feet. In *Professional*



DIAGRAMMATIC SECTION OF UPPER CRETACEOUS FORMATIONS IN TENNESSEE
FROM NORTH TO SOUTH

FIG. 2

LEGEND

E_1 Eocene, Porters Creek clay, "soapstone"
C_9 Ripley, Owl Creek horizon, fossiliferous sandy marl
C_8 Ripley, McNairy sand member, sands, clays
C_7 Ripley, ferruginous clays of McNairy County
C_6 Ripley, Coon Creek horizon, fossiliferous sandy marl
C_5 Ripley, unfossiliferous sands and clays
C_4 Selma, chalky clays varying to micaceous sandy clays
C_3 Eutaw, Coffee sands and black clays
C_2 Eutaw, Tombigbee sand member with few fossils
C_1 Tuscaloosa, gravels
P_1 Paleozoic limestones, cherts, and shales

MARINE FOSSIL LOCALITIES

1 Blue Cut on M. & O. R.R. at Tenn.-Miss. line
2 Trimms Mill, 3 miles east of Middleton
3 Sand Hill, 11 miles southeast of Selmer
4 Florence Road, 5 miles east of Nixon
5 Bear Creek, 2 miles southwest of Victory
6 Coon Creek, 3½ miles south of Enville
7 Shady Hill, 10 miles southeast of Lexington
8 Perryville Road, 7 miles east of Lexington
9 Cub Creek, 1 mile south of Poplar Springs
10 Yellow Spring Road, 5 miles south of Holladay
11 N. C. & St. L. R.R. Cut, 2½ miles west of Camden
12 Dickerson Place, 4 miles north of Camden

FOSSIL PLANT LOCALITIES

I Big Cut, 1½ miles west of Cypress
II New Bethel Road, 2½ miles southwest of Selmer
III John Boyd Place, 5 miles northeast of Selmer
IV Coffee Bluff, 4 miles north of Savannah
V Jacks Creek Road, 4 miles south of Mifflin
VI Perryville Road, 1 mile north of Beacon
VII Huntington Road, 1¼ miles southwest of Buena Vista
VIII Cooper clay pit, 1½ miles south of Hollow Rock
IX Perry Place, 10 miles east of Paris

QUARTZITE LOCALITIES

A Saints Chapel, 6 miles south of Lexington
B N. C. & St. L. R.R., 1 mile west of Lexington
C Big Rocks, 4 miles northeast of Westport
D Hollow Rock, ½ mile west of Hollow Rock Junction
E Elkhorn and Dulac Road, 4 miles north of Elkhorn

Paper 81 of the U.S. Geological Survey L. W. Stephenson has readjusted the nomenclature of the Upper Cretaceous in this region and has defined the Tuscaloosa with reference to the other formations of this series.

Toward the north the Tuscaloosa deposits become much thinner and are made up almost entirely of conglomerates which contain little sand and clay. Professor E. W. Berry[1] has made a study of this series and has found evidence in the fossil plants that the clays, in the basal part of the formation in the region of maximum thickness, are more ancient than plant-bearing clays that occur in the conglomerates about Iuka in northeastern Mississippi where the formation becomes much thinner. He shows that an Upper Cretaceous estuary existed for a long time in western Alabama before it transgressed into the northern part of Mississippi and Alabama.

Until recently the Tuscaloosa formation was thought to thin out entirely in the vicinity of the Tennessee-Alabama line. In 1913 H. D. Miser mapped the areal geology of the Waynesboro quadrangle of Tennessee and found that the Tuscaloosa was one hundred and fifty feet[2] thick and extended over a large part of Wayne County. Subsequent work by the Tennessee Geological Survey showed that remnants of the Tuscaloosa gravel occur in place of the highland rim of Tennessee as far north as northern Lewis County.[3] Farther north, during the summer of 1916, the writer encountered undescribed occurrences of the Tuscaloosa formation which show that the sediments of this transgressive phase of the Upper Cretaceous exist in a chain of local outlying areas across the state of Tennessee and as far north as the ridge west of Canton, Kentucky.[3]

An important link in this chain are the gravels which occur locally along the Nashville, Chattanooga and St. Louis Railroad between McEwen and Tennessee City and capping the higher hills

[1] E. W. Berry, *U.S.G.S. Prof. Paper No. 112* (1919).

[2] H. D. Miser, "Economic Geology of the Waynesboro Quadrangle," *Resources of Tennessee*, Vol. IV, No. 3 (1913), p. 107.

[3] Bruce Wade, "Geology of Perry County and Vicinity," *Resources of Tennessee*, Vol. IV, No. 4 (1914), p. 173; "The Occurrence of the Tuscaloosa Formation as Far North as Kentucky," *Johns Hopkins Univ. Cir.* (March, 1917).

in this part of Dickson County, Tennessee. A cut on the railroad about two miles east of McEwen shows, resting on chert of the St. Louis formation, about thirty feet of very compact, hard, white chert gravel which is very typical of the Tuscaloosa belt across the state. No paleontological evidence has been obtained from the gravels about McEwen to determine the age of these deposits, but after a study of the lithology as well as the geographic and topographic relations, the Tuscaloosa age of the McEwen gravels can hardly be doubted. These gravels are made up of well-rounded water-worn pebbles, most of which are one inch or less in diameter, although many are larger, often ranging up to cobbles six inches in diameter. Many individuals approach a sphere in outline, and in this respect they differ from the river gravels which are common in terraces along the western Tennessee Valley. In the river gravels of this region the individuals are often flat, elongated, and subangular. Small discoidal quartzite pebbles are often conspicuous in the terrace conglomerates. The Tuscaloosa conglomerates consist for the most part of pebbles and bowlders derived from the Lower Carboniferous cherts which are common in this part of the Mississippi basin. Water-worn sandstone and iron-oxide pebbles have not been observed in the Tuscaloosa. This is another feature which serves to distinguish the Upper Cretaceous gravels from the more recent terrace gravels in this part of the embayment region, even though the latter may rest directly on the former, as is frequently the case in the western Tennessee Valley.

South of McEwen, as stated above, the isolated Tuscaloosa gravel areas may be traced along the highland rim across Lewis County into Wayne and Hardin counties and farther into Mississippi and Alabama, where they are overlain by marine Eutaw deposits, and consequently paleontologic evidence may be obtained.

The Tuscaloosa extends also north of McEwen. About three miles west of Canton in Trigg County, Kentucky, at a point just east of where the Fulton and Nashville Highway crosses the divide between the Tennessee and Cumberland rivers, is an exposure of Upper Cretaceous which has already been reported. This exposure occurs in the top of the divide, which is probably more than

three hundred feet above the waters of the Tennessee and Cumberland rivers. This divide is a northern extension of the western Highland Rim of Tennessee, and it is probable that further study of the plateau between the Canton and McEwen localities will reveal isolated occurrences of Tuscaloosa that form an almost unbroken chain of the remnants of this formation from Kentucky across Tennessee into Mississippi and Alabama.

A study of a map[1] of the Upper Cretaceous belt of the eastern gulf region shows that the Tennessee River flows from the east into the Cretaceous in northwestern Alabama and then takes a northerly course just east of the Cretaceous across Tennessee and Kentucky. The geological map shows that the wide Tuscaloosa belt in western Alabama and eastern Mississippi disappears entirely just north of where the Tennessee River flows into the belt, and in the same part of the state the Eutaw belt becomes abruptly narrow and disappears long before it reaches the northern limit of Tennessee. It has been previously shown that the Tuscaloosa formation, though probably not as thick and as widespread as in western Alabama and eastern Mississippi, was at one time an important formation and covered large areas in Tennessee and Kentucky, and that the Eutaw formation extended farther east and north of the areas mapped. The erosion of the western Tennessee Valley has almost entirely removed the Tuscaloosa deposits toward the north, and has likewise removed a large portion of the Eutaw deposits, but to a less extent than in the case of Tuscaloosa.

THE EUTAW FORMATION

In the southern part of the state the Eutaw formation is divided into two members: the *Tombigbee sand* and the *Coffee sand.* The former is made up largely of red ferruginous sands that cap the hills of eastern Hardin County and western Wayne County. This member contains a small marine fauna near Burnsville, Mississippi, and fossils from the same horizon perhaps have been collected in Tennessee in Hardin County at a locality about five

[1] L. W. Stephenson, "Cretaceous Deposits of the Eastern Gulf Region," *U.S.G.S. Prof. Paper 81* (1914), map; also E. W. Berry, "Upper Cretaceous Floras of the Eastern Gulf Region," *U.S.G.S. Prof. Paper 112* (1919), map.

miles east of Nixon on the Florence Road and a single species from near the top of the ridge at the head of Bear Creek in Wayne County. Both of these localities are given on the sketch map (Fig. 1). This member is nowhere in Tennessee very sharply demarked from the overlying Coffee member and probably does not extend northward any farther than the northern part of Hardin County.

The *Coffee sand member* of the Eutaw was first recognized and described by Safford and has been discussed by subsequent writers. It is more than two hundred feet in thickness and is typically exposed on the Tennessee River at Coffee Bluff four miles north of Savannah in Hardin County. It is largely a series of stratified and cross-bedded sands and clays. The sands are usually fine and of various colors, often containing an abundance of scales of mica and in places glauconite and pyrite. The sand frequently is interlaminated with thin layers of clay. Dark or black beds of clay containing very fragmentary leaves and often thick beds of lignitized logs or wood fragments are common. Some of the logs are partly or entirely silicified. Many of the larger logs are perforated by the Cretaceous wood-burrowing pelecypod *Teredo irregularis* Gabb,[1] many of which left thin irregular tubes one inch in diameter in the wood. The clays of the Coffee member are highly carbonaceous and contain an abundance of plant remains. Identifiable leaves from these clays are very rare however. Berry[2] has identified sixteen species from Coffee Bluff and ten species from about the same horizon collected at a locality on the Scotts Hill Road five and one-half miles southwest of Decaturville in Decatur County. A small collection of about seven species was made in 1919 from this same member at a locality one mile north of Beacon, Decatur County. Amber is not uncommon in the beds of wood fragments of this member of the Eutaw. A number of small pieces of amber have been collected at Coffee Bluff and at a locality on the Lexington Road two and one-half miles west of Parsons in Decatur County. One of the specimens from Coffee Bluff contains the wings of a Cretaceous caddis fly, *Dolophilus praemissus*

[1] W. H. Gabb, *Jour. Acad. Nat. Sci.*, Vol. IV, 2d Ser. (Phila., 1860), p. 393, Pl. 68, Fig. 19.

[2] E. W. Berry, *U.S.G.S. Prof. Paper 112* (1919), p. 35.

Cockerell,[1] which Professor Cockerell says is the only known specimen of an American amber insect.

Toward the north the Eutaw formation becomes much thinner until in the vicinity of Dulac in the northern part of Henry County near the Kentucky line this formation is only about twenty feet in thickness. At Riverview, a locality about five miles south of Paducah on the Tennessee River in Kentucky, an exposure of 15 feet of typically laminated Eutaw sands and clays may be observed. In the central part of Decatur County, Tennessee, in the vicinity of Parsons and Decaturville, the basal part of the Eutaw contains irregular lenses of fine chert and quartz gravels sometimes several feet in thickness. Some other vicinities in Tennessee where the Eutaw may be studied are Camden, Holladay, Darden, Scotts Hill, Crumps Landing, Pittsburg Landing, Red Sulphur Springs, etc. The general distribution of the formation is given on the accompanying map.

THE SELMA FORMATION

The name Selma was used in Tennessee as a formational name in 1906 by Glenn,[2] who pointed out that the original term, *Selma chalk*, was applied very aptly in Mississippi and Alabama but was inappropriate in Tennessee. The Selma formation, as represented in the northern gulf embayment regions, consists of fossiliferous chalky clays and argillaceous, micaceous sands laid down during the time when the Upper Cretaceous sea was at its maximum stage of transgression. This stage may be traced across the state of Tennessee by its lithology and fauna, separating the underlying Eutaw sands and the overlying Ripley sands. There are no known unconformities in this Eutaw-Selma-Ripley series, which evidently represents a single cycle of transgression and regression of the Upper Cretaceous sea in Turonian and Senonian time. This cycle took place very slowly and probably extended over a long period of time. The cross-bedded largely non-marine sands and clays of the Eutaw represent the advancing stage of this sea. The Selma chalky sediments represent this sea at its maximum expanse

[1] T. D. A. Cockerell, *Proc. U.S. Nat. Mus.*, Vol. II (1916), p. 99, Fig. 6.

[2] L. C. Glenn, *U.S.G.S. Water Supply Paper 164* (1906), p. 26.

at a stage when no coarse detritus was being washed in. Such a sea was especially favorable for the incoming hundreds of marine organisms which developed in great hordes among various forms, especially of mollusca. Conditions favorable for marine life in the extreme northern part of the embayment were not of long duration. Orogenic changes brought in coarse sediments and this sea began to recede, being filled in with sands which make up the Ripley formation. This recession did not take place suddenly and with uniformity but very gradually with some oscillations and sinuosities of the strand line which brought about the various members of the Ripley formation that are well developed in McNairy County and in the northern part of Mississippi.

The Selma formation is a chalky clay of more than three hundred feet in thickness in the southern part of the state but near the Kentucky line it is less than fifty feet in thickness and is made up of sandy, micaceous clay. This formation is well exposed in the eastern part of McNairy County, giving rise to barren, limy hills known as "bald knobs" or glades that are frequently covered with species of Ostrea, Gryphaea, Exogyra, and Anomia. Toward the north it becomes thinner and loses its chalky nature, yet it may be readily recognized. It may be studied in the vicinity of Chesterfield in Henderson County; about two miles west of Holladay in Benton County; two and one-half miles west of Camden on the N. C. and St. L. R.R. in Benton County; four miles north of Camden on the Big Sandy Road; and about two miles west of Dulac in Henry County. Marine fossils are less abundant in the northern part of the state. In Henry and Benton counties all the exposures of this formation have not yet been examined. Among the collections now at hand for study the most northerly locality at which a collection has been made from this formation is at the Dickinson place four miles north of Camden, Benton County, on the Big Sandy Road. From this locality a fauna of about twelve species has been obtained. Some of the same species with a few additional ones have been collected in the new N. C. and St. L. R.R. cut two and one-half miles west of Camden.

Less than forty species of marine fossils are known from the Selma formation in contrast to more than three hundred and

fifty known from the Ripley formation. This probably does not mean that less than forty species inhabited the Selma stage of the Upper Cretaceous sea in the embayment area, for it is most likely that the widely expanded, quiet, Selma stage of this sea was quite favorable to marine life and that a very large percentage of the Ripley species was inaugurated at that time. It does mean that conditions where so little detritus was being brought in were unfavorable for the preservation of very many Upper Cretaceous species. It may be noted that species of Ostrea, Exogyra, Gryphaea, Anomia, Paranomia, and Pecten are very common in the Selma at many localities. Also it may be noted that the shells of these species are very hard and resistant, being made up of a dense sort of cryptocrystalline shell material which withstood the corrosive and chemical effects of the sea and the attacks of a minute organism, while they were being buried in the very slowly accumulating limy muds. It is true that such species as *Ostrea larva* Lamarck and *Anomia argentia* Morton are thin and fragile, yet they are of a compact shell material and more resistant than such thick shells as a number of species of *Cucullaea*, *Crassatellites*, *Pugnellus*, *Volutomorpha*, etc. Perhaps this point may be brought out by the study of the shell materials and the occurrence of the well-known species *Paranomia scabra* (Morton)[1], which occurs in both the Ripley and the Selma. This bivalve is made up of two distinct shell materials: a thin, hard, compact, resistant outer layer similar to the shell material of certain species of Gryphaea, Ostrea, Exogyra, etc., and a softer inner layer of prismatic calcareous shell material which is similar to the shell material of most of the Ripley univalves and bivalves. In the Selma formation only the thin outer layer of *P. scabra* is found preserved. In the Ripley formation, however, at localities where there are abundant shells of various species unknown in the Selma both the inner and outer layers of *Paranomia scabra* occur perfectly preserved. Thus if the entire shell of this species were as soft as the inner layer this species too would be unknown in the Selma.

[1] S. G. Morton, *Synopsis of the Original Remains of the Cretaceous Group of the United States* (1834), p. 62.

THE RIPLEY FORMATION

The Ripley formation has the greatest areal distribution of any of the Upper Cretaceous formations in Tennessee. It is extensively developed both in the northern and southern part of the state. It outcrops in a broad belt in general along the Tennessee-Mississippi divide, a hilly and sandy area with little fertility or agricultural productiveness. In certain localities this formation is highly fossiliferous and contains an abundance of beautifully preserved animal and plant remains, but these are rather exceptional, for the Ripley of Tennessee is made up largely of non-fossiliferous sands and clays. In the southern part of the state the Ripley formation has been segregated into the following lithologic and faunal members or horizons: Owl Creek horizon or member; McNairy sand member; ferruginous clay horizon or member; Coon Creek horizon or member. In the central and northern parts of the state the Owl Creek member and the ferruginous clay member lose their identity and become a part of the McNairy sand member which constitutes by far the major portion of the Tennessee Ripley.

The Coon Creek horizon or member in the northern part of the state consists of ferruginous sands with few or no fossils, but in the southern part of the state it is glauconitic and fossiliferous. In some localities it contains beds of sandy marl which have yielded a very large fauna of beautiful and unusually well-preserved marine fossils. An announcement of the discovery of these fossils and a somewhat detailed description of the Coon Creek locality together with some preliminary observations on the fauna were published in the March, 1917, number of the *Johns Hopkins University Circular*. Figures and plates of this fauna of about three hundred and fifty species are now being made for a monograph report by the author to be published by the United States Geological Survey.

The occurrence of so many well-preserved shells in deposits as old as the Cretaceous is uncommon. No other single locality in the American Cretaceous, that has yet been studied, has produced so large an assemblage of such excellent fossils, which even rival best Cretaceous collections from any of the well-known European or Indian localities. Some of the well-known Cretaceous localities

that have yielded prolific faunas which may be cited for comparison and reference are: Owl Creek, Mississippi,[1] Ripley formation; Eufaula, Alabama,[1] Ripley formation; Patula Creek, Georgia,[1] Ripley formation; Snow Hill, North Carolina,[2] Black Creek formation; Brightseat, Maryland,[3] Monmouth formation; Mount Laurel, New Jersey,[4] Monmouth formation; Fox Hills, Moreau River, etc., western interior,[5] Montana formation; Huerfano Park, Pugnellus Sandstone, Colorado,[6] Colorado formation; Phoenix, Oregon,[7] Lower Chico series; Queen Charlotte Islands, Canada,[8] Chico series; Ferrocarril de Tampico á San Luis Potosí, Mexico,[9] Lower Senonian; Lastro, Sergipe, Brazil,[10] Senonian; Quiriquina, Chili,[11] Senonian; Pondoland, South Africa,[12] Senonian; Chargeh Oasis, Libyan Desert,[13] Danian; Central Tunis, Africa,[14] Cenomanian Atherfield, England,[15] Wealden; Blackdown, England,[15] Upper Greensand; Aachen, Germany,[16] Senonian; Kunroed, Belgium,[17]

[1] L. W. Stephenson, *U.S.G.S. Prof. Paper 81*, Tables 2, 8; T. A. Conrad, *Jour. Acad. Nat. Sci.*, Vol. III, 2d Ser. (Phila., 1858), pp. 323–36; Vol. IV, 2d Ser. (1860), pp. 275–98.

[2] L. W. Stephenson, *Upper Cretaceous Paleontology of North Carolina.* Manuscript in press; T. A. Conrad, *Rept. Geological Survey of North Carolina*, Vol. I, App. A (1875).

[3] J. A. Gardner, *Maryland Geological Survey, Upper Cretaceous Volume* (1916).

[4] Stuart Weller, *Pal. New Jersey*, Vol. IV (1907), pp. 128–36, etc.

[5] Meek and Hayden, *U.S.G.S. Terr.*, Vol. IX (1876).

[6] T. W. Stanton, *U.S. Geol. Sur. Bull. No. 106* (1893).

[7] F. M. Anderson, *Proc. Cal. Acad. of Sci.*, Vol. II, 3d Ser. (1902).

[8] J. F. Whiteaves, *Geol. Sur. Can. Meso. Fos.*, Vol. I (1876).

[9] E. Böse, *Instituto Geologico de Mexico*, Bol. 24 (1906).

[10] C. A. White, *Archivos de Museu Nacional do Rio de Janeiro*, Vol. VII (1888).

[11] O. Wilchens, *Neues Jahrb. für Min., Geol., und Pal.*, Band XVIII (1904), p. 272.

[12] H. Woods, *Ann. South African Museum*, Vol. IV, Part VII (1906).

[13] A. Quass, *Beitrag zur Kenntnis der Fauna der obersten Kreidebildungen in der Libyischen Wüste* (München, 1902).

[14] L. Pervinquière, *Etudes de Paléontologie Tunisienne*, Vol. I and II (Paris, 1912).

[15] H. Woods, "Cret. Lamel.," *Pal. Soc. London*, Vols. I, II (1899–1913).

[16] E. Holzapfel, *Palaeontographica*, Bände XXXIV, XXXV (1888, 1889).

[17] F. Kaunhowen, *Palaeontologische Abhandlungen*, neue folge, Band IV (1897).

Maestrichtian; Le Mans, France,[1] Cenomanian; Gosau, Austria,[2] Turonian; Conarapollia, India,[3] Arrialoor group.

An analysis of the Coon Creek fauna and comparisons with related faunas will appear in the monograph report. A new species of Scaphites closely related to the well-known form *Scaphites nodosus* Owen[4] is perhaps as diagnostic and as representative a form as any single species of the Coon Creek fauna that might be mentioned. The *nodose* group of Scaphites are widely distributed in the marine Senonian deposits of the Upper Cretaceous of the world. They have been extensively studied and are an important factor in intercontinental correlations[5] of these deposits.

The ferruginous clay horizon or member of the Ripley is well exposed in a cut on the M. and O. R.R. just south of Falcon in McNairy County. This is a series of stratified micaceous clays about one hundred feet in thickness with numerous concretions of limonite which are very conspicuous on the eroded slopes in the central part of McNairy County. A scant and dwarfed marine fauna has been obtained from this clay in the southern part of the state. Toward the north this clay becomes sandy, loses its identity, and merges into the McNairy sand.

The McNairy sand member is a thick series of non-marine sands and clays with a few irregular occurrences of quartzites. As is shown on the accompanying map the McNairy sand covers a wide belt of the Cretaceous area and is equally developed in both the northern and southern portions of the state. This member was first differentiated and described by Stephenson[6] in 1914. It is typically exposed at a cut on the Southern Railroad near

[1] A. d'Orbigny, *Paléontologie Française, Terrains Crétacês* (Paris, 1840–60).

[2] F. Zekeli, *Abhandl. der k.k. Geol. Reichs.*, Band I (1852); K. A. Zittel, "Die Bivalven der Gosaugebilde," *Denkschr. d.k. Akad. d. Wissensch. Wien. Math.-nat. classe*, Vols. XXIV and XXV (1865–66).

[3] F. Stoliczka, "Pal. Indica, Cretaceous Faunas, South India," *Geol. Survey India* (1865–70).

[4] D. D. Owen, *Rept. Geol. Sur. Iowa, Wis., Minn.*, p. 580, Table 8, Fig. 4 (1852); F. B. Meek, *U.S.G.S. Terr.*, Vol. IX, pp. 426–30, pls. and figs (1876).

[5] F. Frech, "Ueber Scaphites," *Centralblatt Min., Geol., Pal.*, No. 18 (1915), pp. 553–68; No. 21, pp. 617–21.

E. Kayser, *Lehrbuch der Geologie*, Teil II, 5. Auf., pp. 534–62 (1913).

[6] L. W. Stephenson, *U.S.G.S. Prof. Paper 81* (1914).

Cypress, McNairy County. Clay is mined from the McNairy sand at several localities in Carroll and Henry counties.[1] Conspicuous large masses of quartzite or very hard, fine-grained, white sandstone of irregular occurrence are found at several isolated localities in Henderson, Carroll, and Henry counties in the lower part of the McNairy sand member. The more important quartzite localities are shown on the accompanying map and section. These masses are exceedingly resistant to erosive agencies and are often left lying bare on the surface after the softer sands and clays which formerly inclosed these masses have been washed away. They occur in irregular, cavernous, and often grotesque shapes that attract the attention of travelers and the natives in these regions. The well-known "hollow rock" at Hollow Rock Junction in Carroll County has served as a landmark since early settlers first went into that part of the state. The most extensive occurrences of this quartzite are two miles south of Dollar in Carroll County where masses as large as a two-story house may be observed in an area of two or three square miles. The origin of these masses is due to the cementation of local accumulations of very fine and pure quartz sands deposited along with the other McNairy sediments. Large masses of highly ferruginous hard sandstones are common in the Ripley, but the quartzites under discussion are characterized by a very low iron content. Similar occurrences of quartzites are known in the Eocene of Tennessee, Arkansas, and Mississippi.

Fossils are quite rare in the McNairy sand, and the few that have been known until quite recently were about twelve species of plants collected from near Selmer[2] and Big Cut[2] in McNairy County and three species from the southeastern part of Henry County.[2] In 1919 Schroeder noted the abundance of fossil leaf impressions in the Cooper clay pit[3] near Hollow Rock, Carroll County, but made no collection of these plants. During the latter part of the summer of 1919 the writer made large collections of

[1] W. A. Nelson, *Tenn. Geol. Sur. Bull. No.* 5 (1911).

[2] E. W. Berry, *Torrey Bot. Club Bull.* 43, pp. 283–304 (1916); *U.S.G.S. Prof. Paper 112*, pp. 38, 39 (1919).

[3] R. A. Schroeder, "Res. of Tenn.," *Tenn. Geol. Sur.*, Vol. IX, No. 2 (1919), p. 154.

fossil plants from the Cooper clay pit and from some new localities, namely, three miles south of Mifflin in Chester County, near Beuna Vista in Carroll County, and from the Perry Place, ten miles east of Paris on the Manlyville Road, in Henry County. These collections have all been submitted to Professor Berry, and he is now completing a monograph report on this heretofore unknown, large, Ripley flora of more than one hundred and twenty species. The majority and the best specimens of this plant material came from the Perry Place. This locality is a small gully exposure of a lens of clay several feet in thickness on a farm belonging to Dr. J. R. Perry. The fossil leaves occur in a two-foot layer of dark brownish clay in the very bottom of the gully. This locality is about eighteen miles southeast of Puryear and about the same distance northeast of the Grable clay pit. Puryear is an Eocene plant locality made famous by the recent studies of Professor Berry,[1] who has collected and described from the Wilcox clays of Puryear the largest and most beautiful fossil flora known in America. The Grable clay pit is a recent opening in the Wilcox clay about twenty miles southwest of Puryear and contains a great wealth of fossil plants. Due to the recent workings at the Grable and due to the filling in of some of the old classic pits, there is at present no locality in west Tennessee where so many beautiful fossil plants can be obtained as at the Grable pit and the neighboring Adkins pit. Of the Ripley plant localities next to the Perry Place in importance is the Cooper clay pit. All the McNairy plant localities are shown on the accompanying map and diagrammatic section.

Stratigraphically above the McNairy sand member in southwestern McNairy and eastern Hardeman counties is the Owl Creek horizon or member. This is a series of micaceous sands and marls about fifty feet in thickness in Tennessee that contain a portion of the Owl Creek marine fauna. About fifty species have been collected at Trimms Mill and other localities on Muddy Creek in Hardeman County. Among these is the Owl Creek form, *Scaphites iris* Conrad.[2] This northern extension of the Owl

[1] E. W. Berry, *U.S.G.S. Prof. Paper 91* (1916).

[2] T. A. Conrad, *Jour. Acad. Nat. Sci.*, Vol. III, 2d Ser. (Phila., 1858), p. 335, Pl. 35, Fig. 23.

Creek beds does not extend far into Tennessee. It is merely one of the major oscillatory stages of the retreating Ripley sea as it withdrew slowly from the northern part of the Mississippi embayment area.

The general stratigraphic and areal relations of the Tennessee Upper Cretaceous are best summarized on the accompanying map and diagrammatic section. These show the positions of the large Ripley faunas and floras with reference to the rest of the Tennessee Cretaceous. The most important scientific results of the recent studies of the Tennessee Cretaceous are the unearthing of the Coon Creek fauna and the Perry Place and Hollow Rock flora. These abundant and excellent animal and plant remains are of nearly the same age and at the base of the Ripley. They not only mark definitely the lower Ripley with two different lines of evidence, making this a very important horizon for reference in subsequent studies and intercontinental correlations of the Upper Cretaceous, but also these well-preserved remains furnish certain biological evidences that are of some importance in the systematic classification of a few of the ancient animals and plants of Cretaceous times.

THE CHESTER SERIES IN ILLINOIS

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PART II

UPPER CHESTER GROUP

Tar Springs sandstone.—Like the Lower and Middle Chester groups the Upper Chester is initiated by an important sandstone formation which is named the Tar Springs. This name was first used by Owen many years ago for a sandstone in Breckinridge County, Kentucky, and has been revived by Butts[1] at a recent date. This sandstone is a persistent formation across Hardin, Pope, and Johnson counties, as far as the detailed mapping has been carried, and it doubtless continues into Union County. The sandstone is variable in character. In some places in the area which it occupies it is as massive and as conspicuous a cliff maker as the Cypress; this is especially true in some portions of Hardin County. Elsewhere it is nearly all thin-bedded. Much of the sandstone is conspicuously cross-bedded. Throughout much and perhaps the whole of the Chester belt across the southern counties, the Tar Springs sandstone is divided into an upper and lower member by a persistent shale bed, which has associated with it in widely separated localities a thin layer of impure coal, in some places only an inch or two in thickness but elsewhere a foot or more. The more massive layers of the sandstone resemble the Cypress and Hardinsburg in color and texture, but in much of Pope and Johnson counties, where the formation is more thinly bedded, it is distinctly darker brown than any of the older Chester sandstones.

The thickness of the Tar Springs sandstone varies considerably. In Hardin County it is one hundred feet or more thick, perhaps as much as one hundred and fifty feet locally, but it diminishes to

[1] *Mississippian Formations of Western Kentucky* (1917), p. 103.

the west, and in western Johnson County there are places where it is apparently not more than forty feet. In tracing the horizon into the Mississippi Valley counties, the Tar Springs disappears entirely, there being not even such a thin discontinuous sandstone horizon as that which represents the Hardinsburg, the position of the sandstone being occupied by a plane of unconformity above the Upper Okaw or Glen Dean limestone.

Vienna limestone.—The Vienna limestone is named from Vienna, Johnson County, Illinois, where the formation is exposed in some of the streets of the town, and in an old quarry just west of the town. As it is commonly exposed, the Vienna exhibits two rather distinct facies, an exceedingly siliceous limestone in the lower portion of the formation, and a shale member above. In places the limestone seems to comprise the greater portion of the formation, but in other localities it is mostly all shale, with but little of the limestone present. As already stated the limestone is remarkably siliceous. The silica is in part in the form of chert layers, and in part is finely disseminated through the limestone. On weathering, the limestone with the disseminated silica loses the lime by solution, and the residuum is a light, yellowish-brown, porous rock, which on first inspection resembles a fine-grained sandstone, but which contains no sand grains whatever. The chert of the formation is quite persistent in character, the beds commonly being from one to four inches thick and quite regular. Near the surface the upper and lower portions of these chert beds have been subjected to some decomposition and are much lighter in color for a fraction of an inch in depth than is the deep chocolate brown of the central portion of the beds. As the limestone with the chert layers is removed by weathering, the cherts fracture into subcubical masses with two light-colored surfaces, and occur in abundance in the residuum. Less commonly there are some thicker chert beds, six to eight inches, which are more or less porous in character. The peculiar character of the weathered products of the Vienna limestone make it about the easiest to recognize of any of the limestone formations of the whole Chester series. The shales of the Vienna are black, fissile, and non-calcareous.

The siliceous limestone facies of the Vienna has been recognized from eastern Pope County, across Pope and Johnson counties, and into the eastern part of Union County, except where the formations are interrupted by faulting. The black shale facies of the same formation probably extends eastward beyond Pope County into Hardin. It has been recognized considerably farther west in Union County than the limestone, but it is not unlikely that the limestone will be found to extend farther in that direction when the detailed mapping is carried across Union County.

North of Golconda, in Pope County, a measured section through the Vienna formation gives a thickness of seventy feet. This is perhaps the maximum thickness that is known, and the average thickness throughout the area occupied by the formation is probably about sixty feet, perhaps becoming considerably thinner than this to the east.

The fauna of the Vienna limestone has certain characteristics which distinguish it from the other limestones of the Chester series. The *Prismopora* so characteristic of the Glen Dean limestone is present somewhat commonly in the Vienna in places, but it has never been observed to be so abundant as it is in some localities in the older formation. Associated with the *Prismopora* there is found somewhat rarely the pelecypod species *Sulcatopinna missouriensis*, which is highly characteristic of the next higher limestone in the Chester series, the Menard. This notable mingling of the Glen Dean and Menard species is perhaps the leading characteristic of the fauna as a whole, although further studies of the fauna must be made.

In the absence of any representative of the Tar Springs sandstone in the Randolph County section, the determination of the Vienna equivalent in the section, if there is such an equivalent, is rendered somewhat difficult. There is no lithologic unit present in Randolph County similar to the siliceous limestone of the Vienna, and no fauna has been recognized in which the Glen Dean and Menard forms are associated. There is, however, locally at least, lying above the Okaw limestone and beneath the typical Menard, a conspicuous black-shale horizon, which may be a continuation of the black shale of the Vienna in the southern

counties. Further field studies may serve to prove or disprove this suggestion.

Waltersburg sandstone.—On Bay Creek, between Simpson and Grantsburg, near the line separating Pope and Johnson counties, there is a conspicuous sandstone formation overlying the Vienna limestone. The maximum thickness of this sandstone along Bay Creek is about sixty or seventy feet, but it is reduced in thickness both to the east and to the west. In an easterly direction the sandstone has been recognized at its proper position in the section nearly to Grand Pierre Creek in eastern Pope County. To the west it is known to extend, but much reduced in thickness, nearly to the Johnson–Union County line, and it may be found to continue into Union County. As viewed along an east-west section across the southern counties of Illinois, this formation is a lenticular body of sandstone with a lateral extent of nearly forty miles. The extent of the formation in a north-south direction is not known.

The importance of this unit in the Chester section was first recognized in Pope County, northwest of Golconda, where it is well exposed in the road just north of Waltersburg, from which locality the formation has been named, although it is by no means as thick at this point as it is farther west. In its area of maximum development the Waltersburg is a massive, cliff-forming sandstone, not conspicuously different in character or appearance from portions of the Bethel, Cypress, Hardinsburg, or Tar Springs sandstones. Where the formation approaches its lateral limits to the east and west, it is a thinly bedded, rather impure sandstone, in layers two or three inches thick, which are commonly distinctly jointed in two directions, one set of joints being placed at intervals of two or three inches, the other at a foot or more. These two systems of joints cause the rock layers to break up into elongate, splinter-like blocks which are rather characteristic. There are places where the entire formation is represented only by two or three feet of sandstone of this character, situated between the black shale of the Vienna below and the calcareous shales and limestones of the Menard above.

No fossils have actually been observed in the Waltersburg, but trunks of Lepidodendron, such as are found in the other Chester sandstones, may be expected.

Menard limestone.—The Menard limestone was originally named from the exposures in the Mississippi River bluffs at Menard, Illinois.[1] The formation is a persistent one in the Chester section of the Mississippi River counties of Illinois, from the point where the formation is first exposed from beneath the overlapping Pennsylvanian formations in Randolph County to where it passes beneath the surface in the Mississippi River bluffs in Jackson County. In the Mississippi River counties, where it was first described, the Menard was found to rest upon the Okaw limestone, the two limestones being rather sharply differentiated by both lithologic and faunal characters. It is now known that two important sandstone formations, the Tar Springs and the Waltersburg, are intercalated between these two limestone horizons in the Chester section of the southern counties, and also the Vienna limestone, unless it can be shown that this formation is represented by the black-shale bed that is at least locally present in Randolph County between the top of the Okaw limestone and the base of the more typical portion of the Menard.

In its typical expression the Menard is evenly bedded in layers about one foot, more or less, in thickness. The individual beds are separated by thin shaly seams or by beds of shale up to several feet thick, the surfaces of the limestone layers being distinctly hummocky. The limestone itself is commonly compact in texture, almost lithographic in places, hard and rather tough, breaking with a splintery or conchoidal fracture. The color of the limestone is commonly light gray, and the weathered surfaces are smooth in most places. These characteristics are quite in contrast with the crystalline beds of the Okaw limestone, with its more roughly weathered surfaces. An occasional bed of crystalline limestone is met with in the Menard, which might be mistaken for the Okaw if it were found alone.

Where the Menard limestone is exposed in the Chester belt across the southern counties, it can be easily traced across Union, Johnson, Pope, and Hardin counties, except where it is interrupted by faulting. Throughout this belt the limestone exhibits essentially the same lithologic characters as in Randolph County,

[1] Weller, *Trans. Ill. Acad. Sci.*, Vol. VI (1914), p. 128; also *Ill. State Geol. Surv.*, Monog. I (1914), p. 28.

except that the freshly broken rock is commonly darker in color, in some places nearly black, and it is associated with a greater amount of shale, one of the most calcareous shale beds at the base of the formation being highly fossiliferous. Near or perhaps at the very base of this limestone in the southern counties, a thin seam of impure coal, not more than two or three inches thick, has been observed in a number of localities and is perhaps a persistent band. A small amount of chert is present in the Menard, by no means so great a quantity as in the Vienna, but distinctly more than is commonly present in the Middle Chester limestones.

The fauna of the Menard possesses many characteristics common to the Chester formations generally, but certain other features differentiate it quite sharply from those of the earlier limestones of the series. The species of the two genera *Spirifer* and *Composita* show a notable change in the Menard faunas from the earlier forms, in being larger and more robust in form. The typical examples of *Spirifer increbescens* are initiated in this horizon, and the typical *Composita subquadrata* takes the place of *Composita trinuclea*, which was the usual form in the older limestones. A very characteristic member of the fauna is the pelecypod *Sulcatopinna missouriensis*, which occurs in most Menard collections; in places it is very abundant, commonly standing vertically in the limestone strata, probably the position it occupied when living. This species occurs also in the Vienna limestone, but more rarely than in the Menard, where it is associated with the bryozoan *Prismopora serrulata*, which is unknown in the Menard. The most fossiliferous horizon in the Menard is the basal calcareous shale which is present in the southern counties, and which has been recognized across Hardin, Pope, Johnson, and Union counties. This bed is similar in character, both lithologic and faunal, irrespective of whether the underlying Waltersburg sandstone is thick, thin, or absent from the section. Among other forms which are commonly met with in this basal horizon is the blastoid *Pentremites fohsi*, and in the experience of the writer this species has been found in no other horizon.

The thickness of the Menard limestone in the Mississippi River counties commonly varies between sixty and eighty feet,

but in the Kiskaddon well, near Bremen, there are eighty-five feet of strata referable to the formation. The average thickness may be assumed to be about seventy-five feet. In the southern counties the formation is somewhat thicker. In one measured section north of Golconda it is essentially one hundred feet, and that seems to be about the thickness of the formation commonly represented in the southern belt.

Palestine sandstone.[1]—The Palestine is the first of the sandstone formations of the Chester series which is present with essentially equal development both in the Mississippi River counties and in the southern counties of Illinois. The sandstone resembles the other Chester sandstones in its general features, but in only a few regions does it include notably massive beds, though such beds are present in the vicinity of Chester, Illinois, where it has been quarried for building stone. In general this sandstone is rather thinly bedded, in some regions including much shale which is more or less arenaceous in character. As commonly exhibited, the color of this sandstone is somewhat paler than most of the older sandstones of the series, and much of it, at least, is rather finer textured. None of these characteristics, however, are persistent enough to enable the formation to be readily recognized by its lithologic characters, and the only sure means of identifying it is from its relations with either the underlying or overlying limestones. Fossil tree trunks of the genus *Lepidodendron* occur more commonly, perhaps, in the Palestine than in any other sandstone of the Chester series, and one specimen six or seven feet long has been observed. No other fossils have been seen in the formation.

The thickness of the Palestine is not so great as that of some of the earlier Chester sandstones, although its geographic distribution is wider. In two measured sections in the Mississippi River counties the formation is sixty and sixty-seven feet respectively. In some other sections it is probably somewhat greater than this, perhaps as much as eighty feet. In the southern counties the maximum thickness of the formation is eighty feet, but in

[1] Weller, *Trans. Ill. Acad. Sci.*, Vol VI (1914), p. 128; also *Ill. State Geol. Surv.*, Monog. I (1914), p. 29.

places it is considerably less, perhaps being as thin as forty feet in places. The average thickess of the formation throughout its entire extent is approximately seventy feet.

Clore limestone.—The Clore limestone was first described in Randolph County[1], and at the time it was believed to be the highest formation in the Chester series, but later observations have shown that it is succeeded by still another sandstone, and this again by a higher limestone formation. In many places the Clore really includes a larger amount of shale than it does limestone, locally the shale being much in excess of the limestone, and some ledges of the limestone itself are more or less shaly. The limestone beds of the formation exhibit a considerable amount of variation, some being compact and fine grained, others being shaly, some are hard and apparently siliceous, and a few beds are more or less crystalline. Nearly all of the limestone beds are more or less impure. The shale beds are almost entirely argillaceous or are more or less calcareous, the more calcareous beds having thin, platy layers of limestone imbedded in the shale. In the Mississippi River counties there is apparently a greater amount of limestone in the formation than in the southern counties, but wherever the formation occurs it is difficult to determine in detail its true composition, because of its non-resistent character and the consequent covering of surficial material.

The Clore is not a thick formation. Its thickness in two measured sections in the Mississippi River bluffs below the mouth of Marys River is between thirty and forty feet. In places, where it is the uppermost formation in the Chester series, it varies in thickness from forty feet down to nothing, due to the erosion of the higher beds. In the southern counties of the state the Clore is nowhere the highest formation of the Chester, and its lower and upper limits can rarely be determined with exactness. Furthermore both the lower and upper limits of the formation have nowhere been determined in one and the same section with any degree of accuracy. These conditions make the determination of the thickness of the formation in these counties rather uncertain,

[1] Weller, *Trans. Ill. Acad. Sci.*, Vol. VI (1914), p. 129; also *Ill. State Geol. Surv.*, Monog. I (1914), p. 29.

but numerous observations seem to establish a limit of about forty feet for the interval between the underlying and overlying sandstones in which it must be contained, which seems to establish a nearly uniform thickness in both of the two Chester areas of the state. As the formation is traced eastward, in the eastern part of Pope and in Hardin County, the Clore seems to become thinner even than the forty feet of the region to the west.

The fossils of the Clore formation are numerous in places, and, like the faunas of all the other limestones of the Chester series, it possesses certain rather distinctive features. The general composition of the fauna is similar to that of other Chester horizons, being made up largely of bryozoans and brachiopods, with the axes of *Archimedes* and numerous species of Fenestellids being conspicuously present. The most significant feature of the fauna, however, is the abundance of small, cylindrical, branched bryozoa of the genus *Batostomella*, *B. nitidula* apparently being a conspicuous species. The fossils are most abundant upon the surfaces of thin limestone layers imbedded in some of the shales, and one such horizon is rather persistently present near the middle of the formation throughout most of the southern belt, and perhaps also in the Mississippi River counties as well. It is from this layer that the bryozoan-covered slabs of the Clore can be collected in great numbers. Among the brachiopods of the Clore fauna, large forms of *Spirifer increbescens* and *Composita subquadrata*, similar to those in the Menard limestone, are common in some localities.

Degonia sandstone.—During the earlier field studies in Randolph County, it was believed that the massive sandstone formation which was found to overlie the Clore limestone was the basal member of the Pennsylvanian, but during the progress of the field mapping of the Campbell Hill Quadrangle in the summer of 1919 by J. M. Weller, it has been found that this sandstone is succeeded by a still higher Chester limestone, which in turn is overlain by the true lower Pennsylvanian Pottsville sandstone filled with pebbles in many places. This sandstone, now known to be Chester, is especially well exhibited in the walls of several tributaries to the Mississippi River in Degonia Township of Jackson County, Illinois, and the name has been chosen from these exposures.

In southeastern Randolph, and in Jackson County to the valley of the Big Muddy River, the Degonia is a conspicuous cliff-forming sandstone, well exposed in the Mississippi River bluffs and in some of the tributaries to the Mississippi. In its massiveness the formation is perhaps more nearly comparable with the Cypress sandstone of the southern counties than with any other Chester sandstone, and where it is best exhibited it is commonly exposed in vertical cliffs forty or fifty feet in height, although the total thickness of the formation is considerably greater than this. The sandstone is somewhat coarser than most if not all of the other Chester sandstones, and is so much like some of the lower Pottsville beds of the adjoining regions, in localities where such beds are free from pebbles, that it is impossible, in places where the Kinkaid limestone is wanting, to always establish the line separating the Degonia from the Pottsville. Indeed this whole sandstone formation was considered to be Pottsville by Shaw, and was so mapped in the Murphysboro Quadrangle.[1]

In some sections, and perhaps in all, the whole of the Degonia is not as massive as the conspicuous cliff-making beds of the formation, but consists of thinly bedded or almost shaly sandstone in which the individual beds are undulating or curling, the undulations being irregular in character and having a width of only a few inches and a height of an inch or two. In places the more massive layers and the thinly bedded layers are arranged alternately in the sections, the units being variable in thickness up to fifteen or twenty feet. The total thickness of the Degonia sandstone throughout its extent in Randolph and Jackson counties varies only slightly from one hundred feet except where it is the highest formation in the Chester series and has been subjected to pre-Pennsylvanian erosion.

Of all the Chester formations the Degonia sandstone is most nearly continuous from the Mississippi River counties into the more southern area of the state, and further field studies may establish the complete continuity of the formation from one area into the other. In Jackson County the formation has been traced southward to the valley of the Big Muddy River. It is

[1] *Geologic Atlas of U.S.*, Folio No. 185 (1912), p. 6.

undoubtedly present in the Mississippi River bluffs south of the Big Muddy, and probably can be traced to northwestern Union County, where it will connect with the belt across the southern counties.

In the southern counties the Degonia is continuously exposed from Union to Hardin counties. In Union County the thickness of the formation is in excess of seventy-five feet; at Simpson, in eastern Johnson County, it is at least one hundred feet thick; but farther east, across Pope and Hardin counties, it probably is somewhat reduced from the maximum thickness. There are places in Union County where the formation is fully as massive as in any of the sections in Jackson County, but to the east it becomes somewhat more thinly bedded, although massive layers are present in the formation throughout its entire extent in the state. In general, in its more eastern extension, the Degonia sandstone is rather paler in color and of finer texture than farther west, and in many places it resembles the Palestine somewhat closely.

The fossils of the Degonia sandstone are like those of the other Chester sandstones. The only forms that have been recognized are plant remains, and of these the *Lepidodendron* trunks are most commonly met with.

Kinkaid limestone.—The highest formation in the Chester series of Illinois is the Kinkaid limestone, named from the excellent exposures on Kinkaid Creek, in Jackson County. The formation is well developed in southeastern Randolph and in Jackson counties, and continues across the southern counties from Union to Hardin.

In its lithologic characters the Kinkaid more closely resembles the Menard than any other Chester limestone. It has been deposited in the same sort of regular beds about a foot, more or less, in thickness, the individual beds being separated by thin shaly seams, and the surfaces being distinctly hummocky. Many small exposures of the Kinkaid would be indistinguishable from similar exposures of Menard if the stratigraphic relations could not be determined. Some of the beds of the Kinkaid possess the same sort of compact, hard, close-textured limestone that is so commonly present in the Menard, but on the whole the Kinkaid probably includes a larger amount of somewhat more crystalline limestone

than the Menard. In Randolph and Jackson counties no notable shale members have been recognized in the formation, and no conspicuous chert layers have been seen in place, although in some localities the residuum from the formation shows a considerable amount of broken chert.

In the southern counties the Kinkaid limestone is similar in character to the exposures in Jackson County; this is especially true in Union County, but as the formation is traced to the east it is found to include important shale beds and some very notable chert horizons. A very characteristic shale bed in the Kinkaid in Johnson and Pope counties, and perhaps also in Hardin, near the base of the formation and some eight or ten feet thick, is a dark-red color. There are perhaps other red-shale horizons in the formation. Other shale beds are of a distinctly olive-green color, and these red and green shales are a very characteristic feature of the formation in the more eastern portion of its extent. In this same region there are one or more remarkable chert horizons in the Kinaid. The more important of these is a massive bed three or more feet thick, commonly rather light colored, and in places with a slightly greenish tint. The resistant character of this chert makes it a conspicuous feature in places in the residuum from the formation as seen along roadsides, in stream beds, and on hillsides. In places subcubical masses of the chert a foot or more in dimension are strewn over the surface where the bed is present. There are other less conspicuous chert beds, some of them dark colored and similar in character to the chert that is so abundant in the Vienna limestone. The limestone layers of the Kinkaid in this more eastern region are quite similar in lithologic character to the beds in Randolph and Jackson counties.

The thickness of the Kinkaid limestone exhibits considerable variation due to the fact that it is the highest formation of the Chester series, and has consequently been subjected to the pre-Pennsylvanian erosion. Its greatest thickness in Jackson County is in excess of fifty feet, and it may vary from this maximum thickness to nothing at all, for in places the Pennsylvanian strata rest upon the Degonia sandstone. In the southern counties the formation is also variable in thickness, but on the whole it is notably

thicker than it is north of Big Muddy River. At one locality in the bluffs northwest of Buncombe, in Johnson County, the limestone is about one hundred and forty feet thick and in the entire belt across the state the minimum thickness seems to be not less than sixty or seventy feet.

The fauna of the Kinkaid limestone, so far as it is known, is not so prolific as is that of several of the older limestones in the Chester series, but it resembles these earlier faunas in its general characters, consisting, as it does, of the same genera of brachiopods bryozoans, and blastoids. The pelecypod *Sulcatopinna missouriensis*, which is so characteristic of the Menard, is also present in the Kinkaid, and associated with it is the large form of *Spirifer increbescens*. The specimens of *Composita*, however, which have been met with in the Kinkaid, are of the smaller type, like those in the Middle and Lower Chester limestones. A form that is very common in the Kinkaid is a species of *Martinia*, a genus which is commonly wanting in other Upper Chester faunas, and is only locally common in the Middle and Lower Chester horizons. The bryozoans have nowhere been found to be so abundant or so well preserved in the Kinkaid as they are in the earlier Chester limestones, but those that are present are members of the same genera as are represented elsewhere, and most of the species are also believed to be present in the lower horizons.

GEOLOGICAL CROSS-SECTION

The relations of the several Chester formations in Illinois which have been described in the preceding pages are shown in the accompanying diagrammatic section. This section is intended to illustrate the sequence of beds from Hardin County at the southeast to Randolph and Monroe counties at the northwest. The sandstone units are shaded in the diagram, the limestone-shale units being left blank. The diagram has been constructed as if the upper units of the formational succession were continuous to the extreme northwestern extension of the Chester beds in St. Clair County. This is not the actual condition, however, for the entire series of beds is truncated by the Pottsville, so that these basal Pennsylvanian strata, in passing northward from Randolph

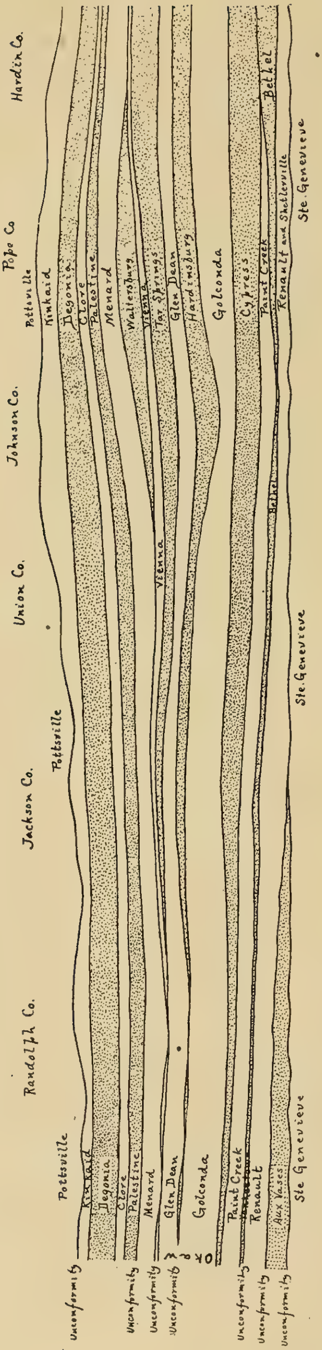

FIG. 1

through Monroe and into St. Clair counties, successively overlap the truncated Chester formations until they rest upon the Ste. Genevieve and St. Louis limestones whose position is beneath the Chester.

GEOLOGICAL HISTORY

In order to appreciate properly the historical relation of the Chester series in the Illinois basin to the Mississippian as a whole, it is desirable to outline somewhat briefly the succession of events which are recorded in the Lower Mississippian or Iowa series. The stratigraphic units which are commonly recognized in this series in the Mississippi Valley are as follows:

7. Ste. Genevieve limestone
6. St. Louis limestone
5. Spergen limestone
4. Warsaw limestone and shale
3. Keokuk limestone
2. Burlington limestone
1. Kinderhook group

Throughout this basin the oldest of the Mississippian formations belonging to the Kinderhook group rest unconformably upon whatever beds underlie them, unless possibly there may be a continuity of sedimentation from Devonian time in southeastern Iowa. There is some reason to believe that the oldest Kinderhook

beds at Burlington, Iowa, the blue shales beneath the Chonopectus sandstone, are continuous with the Sweetland Creek shales which commonly have been placed in the Upper Devonian. However, the Sweetland Creek shales are unconformable upon the beds beneath them, and it is possible that the whole of the Sweetland Creek shale should be placed in the Mississippian. This condition of unconformity of the Kinderhook upon underlying formations of various ages persists entirely around the Ozark region of Missouri and northern Arkansas. This situation shows that preceding Kinderhook time the waters were withdrawn from the Mississippi Valley basin, at least north of the Ohio River, and possibly were withdrawn from the entire continent. The details of the first advance of the Mississippian waters cannot be discussed in this place, but the sediments recording this epoch are exceedingly various in character, there being sandstones, shales, and limestones. As the waters advanced the Ozark land mass was at last largely or perhaps wholly submerged, and the mainland shore line of the Illinois basin crossed northern Illinois or southern Wisconsin and continued westward into Iowa. The position of this shore line was certainly north of Chicago, as is evidenced by the typical Lower Burlington fauna which has been recorded from the northern part of that city.[1] At this time the waters covering southeastern Iowa, the Ozark region of Missouri, and the adjacent parts of Illinois were quite free from land wash, and the very pure Burlington limestone was being deposited throughout this region. During Keokuk time there was a shifting of the northern shore line in a southerly direction, to such a position that a certain amount of clastic material was washed into that part of the sea which covered southeastern Iowa and the adjacent parts of Missouri and Illinois. The presence of this land wash is shown in the shaly beds which are present in the more northerly Keokuk exposures, a lithologic character which differentiates the Keokuk from the underlying Burlington limestone. Farther south in Illinois and in Missouri, both in the southeastern and southwestern parts of the state, at a greater distance from the shore line, these clastic beds are not present in the Keokuk, a condition that

[1] Davis, *Jour. Geol.*, Vol. XXV (1917), pp. 576–83.

makes the lithologic separation of the Burlington and Keokuk somewhat difficult.

In southeastern Iowa the land-derived sediments became more dominant in Warsaw time, although there is no stratigraphic break between the Keokuk and the Warsaw. Farther south in the Mississippi Valley basin, limestone deposition continued into Warsaw time, and in southwestern Missouri shale deposition of this age is absent or practically absent throughout the entire epoch. During Warsaw time, however, the northern shore of the basin continued its southward migration and by mid-Warsaw time it doubtless occupied a position somewhere between the southern border of Iowa and St. Louis, Missouri, and at this time the clastic sediment extended as far south as southeastern Missouri. The lower Warsaw only, therefore, was deposited in southern Iowa.

During Spergen time the sea readvanced to the north and again occupied what is now southeastern Iowa, where the Spergen limestone rests unconformably upon the Warsaw and where locally much or all of the lower Warsaw that had been deposited was eroded during the time when the shore line occupied a more southern position and when this part of Iowa was an area of dry land. At St. Louis and to the south the Warsaw sedimentation passed without interruption into the Spergen, but with the northward shifting of the shore line of the basin and the consequent greater remoteness of the region from the source of land wash pure limestone sedimentation without clastic materials of any sort was reinitiated.

During the later portion of Spergen time the shore line again shifted to the south, and must have occupied about the position of the late Warsaw land margin. This was followed by another shift to the north, which is evidenced by the unconformable relations of the lower St. Louis in Iowa, resting upon the eroded surface of the Spergen, the erosion in places having even cut through the Spergen, so that the higher formation rests upon beds of Warsaw age. Another oscillation of the shore line occurred in mid-St. Louis time, for the upper St. Louis beds in Iowa are separated by a distinct erosional unconformity from the lower St.

Louis, and this stratigraphic break is probably exhibited in the very greatly brecciated zone in the midst of the St. Louis limestone as far south as Alton, Illinois.[1]

In the region south from St. Louis, during all this time, the sedimentation had been continuous with no interruption whatsoever, showing that the Mississippian sea had continually occupied this southern portion of the basin. At the close of St. Louis time, however, a greater oscillation in the sea-level occurred, and the waters were withdrawn to some extent from the Ozark land as well as from Iowa and from all of the region between Iowa and Ozarkia. This withdrawal was only temporary, however, for the sea reoccupied the entire region and in it the Ste. Genevieve limestone was deposited unconformably upon the St. Louis. This sub-Ste. Genevieve unconformity is well exhibited near Ste. Genevieve, Missouri, and wherever the Ste. Genevieve limestone is present to the north of this locality to its most extreme northern outcrops in the Des Moines Valley of Iowa, near Fort Dodge. In a southeasterly direction from Ozarkia, however, in Hardin County, Illinois, sedimentation was continuous from the St. Louis into the Ste. Genevieve limestones, with no interruption of any sort, showing that the Mississippian sea continuously occupied this portion of the Illinois basin. The record of the extension of the Ste. Genevieve sea to the north and west of Ozarkia is obscured by the presence of younger sediments, but it is not unlikely that this ancient island was entirely surrounded at this time. Following Ste. Genevieve time the sea withdrew completely from the Illinois basin. Wherever the Chester formations are present their faunas appear abruptly, and wherever the sections have been examined critically there is evidence of unconformity between them and the underlying formations.

In summing up the history of the Illinois basin in Lower Mississippian time, the succession of events consists of oscillatory movements of the sea occupying the basin, these oscillations being exhibited by the shifting of the bounding shore line of the basin from north to south and back again to the north. The greatest

[1] These statements concerning the stratigraphic relations in southeastern Iowa are based chiefly upon the field observations of Dr. J. M. Van Tuyl.

northern extension of the basin was early in Mississippian time, the successive reoccupations of the region perhaps falling a little short each time of the previous one, and the successive withdrawals perhaps being a little greater each time until the final withdrawal at the close of Ste. Genevieve time. With each readvance of the sea to the north, however, essentially the same basin was reoccupied, so that the sea-pattern during all of this time, in the periods of greater submergence, remained practically the same, differing only in more or less minor details. During each interval of submergence in this period, the sea spread far to the north in Illinois, and westward in Iowa, and doubtless also in northern Missouri, surrounding and perhaps completely submerging at times the Ozark Island, and doubtless was connected with the seas which extended westward to the Rocky Mountain land.

With the return of the seas into the Illinois basin at the beginning of Upper Mississippian or Chester time, the conditions indicated by the sedimentary record were very different from those that had existed earlier. In the earlier period almost no sand deposits were accumulated anywhere in the region except in Kinderhook time, during the initial submergence of the basin, the only exception to this being the presence of the thin Rosiclare sandstone layer that is present in the Ste. Genevieve limestone in most sections. In Chester time, as has already been shown in the discussion of the successive formations, thick deposits of sand were accumulated, and most of the limestones were associated with large amounts of clastic material in the form of shales, these shaly Chester limestones being in strong contrast with the great thicknesses of nearly pure, massively bedded limestones of the Lower Mississippian. The original source of all these accumulations of Chester sand is not entirely clear. The Aux Vases sandstone at the base, which is thickest toward the eastern shore of Ozarkia and thins southeastwardly to nothing, may have been derived from the wearing away of some of the more ancient sandstones of Ozarkia, but such sandstones as the Bethel, Cypress, Hardinsburg, and Tar Springs, which are thick formations in southeastern Illinois and beyond in Kentucky, becoming much reduced or even absent altogether toward the shore of Ozarkia, could not have had such

a source. The sand of these formations may have been derived from the Appalachian land, still farther to the east. The Palestine and Degonia sandtones, which are almost equally thick clear across Illinois, belong in still another category. The Waltersburg sandstone differs in distribution from all of the others, being essentially restricted to an area about forty miles in width east and west, with an unknown extent in a north-south direction. This may be an accumulation in the form of a delta at the mouth of some stream from the north, which emptied into the Illinois basin, perhaps bringing the sand from some far-distant region. The origin of such sands as the Palestine and Degonia, which are more uniformly developed across the entire basin, and even some of the others which are less uniformly developed, may have been from more than one source.

The lateral distribution of the sands of the Chester series in the Illinois basin was doubtless through the agency of wave action along the shore line. During the stages of withdrawal of the waters in the basin, those shore sands, left high and dry, would be subjected to erosion and to transportation southward and redeposition, and to re-working in the next following advance of the waters. In this manner the same sand may have been worked over and over again in the shore deposits of the basin, a condition which may account in part at least for the great similarity between the several sandstone formations of the series.

The areal distribution of the Chester formations is very different from that of the Lower Mississippian. The northernmost exposures of the Chester is in the Mississippi River bluff in St. Clair County, Illinois, about one-half mile north of the St. Clair–Monroe County boundary line, opposite Bixby. Beyond this point the Chester formations are covered by the Pennsylvanian, but well records indicate that they swing off to the northeast from the last exposure to the vicinity of Decatur, Illinois, and from there continue in a southeasterly direction, passing into Indiana. These formations, therefore, were deposited in a basin lying between Ozarkia on the west and Cincinnatia on the east, with its northernmost extremity near the center of Illinois. This basin had a very different outline from that in which the Lower Mississippian

beds were laid down, the older basin extending much farther north and reaching westward into northern Missouri and Iowa, probably surrounding or submerging the Ozark land. The sea-pattern, then, of Chester time was quite different from that of the earlier Mississippian. The succession of sandstones and limestone-shale formations laid down in this basin in Chester time indicate a series of oscillations of the sea occupying the basin, comparable in a way to the oscillations in the much larger basin of Lower Mississippian time.

Throughout the alternating succession of Chester formations, the several units should be considered in pairs, each pair consisting of a sandstone formation below, passing upward into a limestone-shale formation. In a number of horizons in the series the sandstone formation clearly exhibits an unconformable contact with the underlying limestone, but in no case is there any evidence of unconformity between the sandstone and the overlying limestone-shale unit. Each one of these pairs doubtless represents one oscillatory advance and retreat of the waters of the basin, the lower sandstone unit in the pair being a transgressing formation associated with the advancing submergence, the limestone and shale deposition lagging behind the sand accumulation at a greater distance from the shore line. In so far as the sandstones lie unconformably upon the underlying limestone the magnitude of the oscillation has been sufficient to cause the waters of the basin to withdraw to a position south of the localities where observations upon surface outcrops have been possible. If the horizons of such unconformities could be traced southward toward the open sea of the period, they would presumably pass into entirely uninterrupted series of sediments, and if they could be followed still farther in the same direction the sandstone members in the succession of beds should disappear and a continuous limestone formation should represent the Chester series. At those horizons where no evidence of unconformity between the sandstone and the underlying limestone exists, the southernmost position of the retreating shore line of the basin was presumably somewhat north of the localities where the outcrops have been observed, and if the position of the ancient shore line at a period of emergence crossed the

present belt of outcrop of the formations, the unconformity might be looked for over part of the area and be entirely absent elsewhere.

With each readvance of the Chester sea in the Illinois basin, prolific invertebrate faunas occupied the waters, and their fossil remains have been preserved in the limestones and calcareous shales. These successive faunas were much alike in many respects, but as they are critically studied, it is found that each one of them possesses certain characteristics which serve to differentiate it from the others. Farther to the south or southwest, beyond the area of alternating land and sea conditions which obtained within the Illinois basin, the Chester fauna was doubtless undergoing a continuous, normal, evolutionary development, and the successive stages of this evolution, modified more or less by the local environmental conditions, are mirrored in the successive faunas of the several calcareous formations in the Chester section of the Illinois basin.

The succession of events that has been outlined has an important bearing upon the interpretation of the Mississippian period of North America. In his "Revision of the Paleozoic Systems," Ulrich[1] has split the Mississippian into two so-called systems, the Waverlyan below and the Tennesseean above, the line of cleavage between the two being placed between the Warsaw and Keokuk formations. From the evidence afforded by the Mississippi Valley section of the Mississippian, which is the type section of these strata, there is less reason for placing a major dividing line at this horizon than at almost any other position in the entire succession of formations, and there is no basis whatsoever for the recognition of the so-called Waverlyan and Tennesseean as systems. There are, however, many excellent reasons for making a lower and upper division of the Mississippian, the line of separation being at the base of the Chester series. This position is approximately at the horizon where Ulrich has subdivided his Tennesseean into the Meramecian and Chesterian, but even here he has made a grave error in including the Ste. Genevieve limestone in the Chesterian. This error was introduced by his failure to separate the Renault

[1] *Bull. Geol. Soc. Amer.*, Vol. XXII (1910), Plate XXIX, opp. p. 609.

limestone of western Kentucky and southern Illinois from the underlying Ste. Genevieve limestone. The Renault, or Renault-Shetlerville, actually lies unconformably upon the Ste. Genevieve in the sections examined by Ulrich, with the Aux Vases sandstone of the Mississippi Valley section wanting. The characteristic Chester fauna of the Renault limestone, mistakenly included in the Ste. Genevieve by Ulrich, led him to assign the whole of the Ste. Genevieve to the Chester. Although there is some passing of species from the Ste. Genevieve into the basal Chester, long experience in the field has demonstrated that the really characteristic Ste. Genevieve fossils species do not pass into the Renault or basal Chester, and long-continued faunal studies based upon extensive collections have shown that by far the most important faunal break in this portion of the stratigraphic sequence occurs in passing from the Ste. Genevieve limestone to the overlying Chester. This important faunal break, associated with the unconformable relation of the Chester sediments upon the underlying formations, wherever this portion of the section is exhibited, and also associated with the distinct change in sea-pattern in passing from the Ste. Genevieve to the Chester in the Illinois basin, seems to afford an abundance of evidence of various sorts for placing the major line of division within the Mississippian at the top of the Ste. Genevieve limestone. In the Mississippi River counties of Illinois this line is at the base of the Aux Vases sandstone, while in the more southern counties of the state it is at the base of the Shetlerville-Renault limestone unit. The two so constituted divisions of the Mississippian are of sufficient importance to rank as series, the Mississippian as a whole constituting a system.

[*Concluded*]

CONCERNING THE PROCESS OF THRUST FAULTING

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The following paper is offered as a contribution to the studies of low-angle faulting which have been led by the researches and teaching of Professor R. T. Chamberlin.

A comparison of this paper with previous publications, especially "Low-Angle Faulting," by R. T. Chamberlin and W. Z. Miller,[1] will show that the writer has followed Chamberlin in large measure. Most of the material here presented has really been anticipated in the article referred to, but a different manner of approach on some phases of the study is attempted, and the possibility is suggested that there may be a closer relationship between low- and high-angle thrust faults than is commonly accepted.

In 1910 Chamberlin[2] published his paper on the structure of the Appalachian Mountains in which he showed reason to believe that the part of the crust affected by deformation is a shallow, wedge-shaped mass about thirty miles deep and about nine hundred miles long. Willis,[3] upon independent but similar arguments, suggested that the depth of the mass deformed in the uplift of the Cascades lies between thirty-seven and one-half and fifteen hundred miles.

So far as the writer knows, these conclusions have been accepted as sound, in spite of the fact that they appear to be fundamentally different from the prevalent notion that mountain folding is relatively shallow and that the deformable crust of the earth is of the

[1] *Jour. Geol.*, XXVI (1918), 1–44.

[2] R. T. Chamberlin, "Appalachian Folds of Central Pennsylvania," *Jour. Geol.*, XVIII (1910), 228–51.

[3] Bailey Willis, *U.S. Geol. Surv., Prof. Paper No. 19* (1903), p. 97.

character of a thin layer or sheet. In a later paper Chamberlin[1] concludes as the result of his work in the Rocky Mountains that the western mountain mass has this generic difference from the eastern range in that it is composed of broadly folded members of very great depth as contrasted with severely folded and faulted members of less depth. Thus following Chamberlin, it seems that there are some cases of mountain folding in which the strains are relatively shallow as well as some cases in which deformation has been much deeper, which may support the theory that faulting and sharp folding may affect a shallow terrain at the same time that deeper parts of the crust are undergoing flow deformation. The observation of Daly[2] that in south central British Columbia the overlying sediments are much more sharply folded than the underlying pre-Cambrian rocks gives further support to this general notion.

In attempting to analyze earth deformation it is natural, erroneously, to consider the deformed parts of the crust as comprising the whole members subjected to stress; whereas such parts are merely those portions of the structural member which failed.[3] In consequence of this, it follows that it is a matter of considerable doubt as to what the nature and dimensions of the structual members may have been. So it comes about that most discussions are based upon an attempted analysis of the strains involved rather than upon the basis of controlling forces. And this is logical enough, in that here and there the strains remain clearly recorded, whereas the stresses and the nature of the members involved can only be inferred. Presumably, if we follow the traditional teachings, the compressive forces are caused by a more rapid decrease in volume of the inner part of the earth than can be accompanied by the solid shell without buckling or breaking, and consequently the whole shell of the earth constitutes the members concerned. However, the earth's crust is sharply divided into continental and oceanic members; whether these members are conceived to be

[1] R. T. Chamberlin, "The Building of the Colorado Rockies," *Jour. Geol.*, XXVII (1919), 248.

[2] R. A. Daly, quoted by C. K. Leith, *Structural Geology* (1913), p. 127.

[3] Cf. Chamberlin and Miller, *op. cit.*, p. 21.

segments or sectors, according to the older and the newer theories respectively, they act as individual components of a single member and as such are subject to separate analyses. Curved, rigid, sheetlike members under lateral compression fail in the center. Apparently the earth members fail by rupture and buckling at the ends or edges,[1] from which it follows, either that the conception of sheetlike members is erroneous, or that the members are not rigid bodies, or both. It is surely a fact that the earth members are not rigid under the conditions of mountain folding; the manner of their failure proves that beyond question. There is still a possibility that under some conditions the forces are transmitted through shell-like members, and that at other times the forces are distributed throughout deep earth sectors. It seems to be probable that both conditions have prevailed repeatedly at different times. Chamberlin's conclusion that the mountain ranges are of two generic types, one with deep and the other with shallow roots, supports this idea. But, however deep the strains may be, it is possible that there is so distinct a zone of shearing between the frangible, nearly rigid crust and the interior which is deformed by flow that the crustal part in any case fairly may be considered an individual member. It is probable that deep-seated strains affect a discontinuous member, plastico-rigid at depth, but more frangible toward the surface,[2] wherefore the term "plastico-frangible," perhaps, might be used to denote the characteristic quality of the outer crust. Objections to these terms arise readily, especially by comparison with the terminology of other writers. T. C. Chamberlin prefers the term "elastico-rigid"[3] because that expression indicates rigidity associated with elasticity in distinction from solidity due to high viscosity. The word "fluidable"[4] has been used to denote the potential fluidity of the earth's interior.

[1] Bailey Willis, "Mechanics of Appalachian Structure," *13th Ann. Rept. U.S. Geol. Surv.*, Part II (1893), p. 247.

[2] Cf. Bailey Willis, *U.S. Geol. Surv., Prof. Paper No. 19* (1903), p. 97, and Joseph Barrell, *Jour. Geol.*, XXIII (1915), 438.

[3] T. C. Chamberlin, *Jour. Geol.*, XXVI (1918), p. 194, and personal communications.

[4] J. W. Gregory, *Geology of Today* (London, 1915), p. 156.

But in this article there is no design either to emphasize the elasticity of the earth as a whole or the liquefaction of local parts, nor on the other hand is there any need to deny the reality of these characteristics. But inasmuch as no term has yet been devised which adequately describes the character of the earth's interior, it is necessary to choose for different purposes different terms emphasizing different phases of the earth's behavior, each admissible term being complementary and not contradictory to the others.

TERRESTRIAL FORCES AND CRUSTAL MEMBERS

The nature of earth stresses.—The usual argument is that there is a more or less rigid, plastico-frangible, unshrinking crust upon a plastico-rigid, shrinking interior. Between the central sphere and its crust, adjustment is made possible by a zone of almost no strain, above which the earth's crust must undergo strain increasing from near zero at the base to a maximum at the surface.[1] Within the zone of flow the strain is accommodated by flow, above that by a combination of flow and shearing.[2] Any thrust that may be applied in a zone of perfect flow cannot be transmitted as such; it is transmitted hydrostatically. However, it is not probable that there is a zone of perfect flow; probably the rock yields under long-continued pressure, whereas, in the manner of tar, it might rupture under a sudden shock. Such shocks are inconceivable as affecting this zone of flow, and for purposes of this discussion the zone of flow may be regarded as one in which there is a minimum of vector or directional forces. Movement of the crust over the shrinking interior would tend to produce displacement in the zone of flow at an angle approaching zero, no matter at what angle thrust forces cause rupture in the upper crust.[3]

A perfectly rigid body transmits thrust in such a way that the forces are not dissipated during transmission. This type of body does not obtain in the earth's crust, for rocks are not perfectly rigid materials. Material which is slightly plastic tends to fail near the points of the application of force instead of near the

[1] T. C. Chamberlin and R. D. Salisbury, *Geology*, II (1907), 127–30.

[2] C. K. Leith, *Structural Geology* (1913), p. 4.

[3] T. C. Chamberlin, "The Problem of Faulting," *Econ. Geol.*, II (1907), 597–99.

center, the part most susceptible in nearly rigid members. Nevertheless, the rocks within a mile of the earth's surface are, in general, more nearly rigid in behavior than those near the zone of flow. Furthermore, there is more force to be transmitted presumably near the surface, because the length of the arc is greater at the surface than near the center, and the accumulative forces are proportional to the length of the arc to be accommodated to the shrinking. Consequently, there is a greater thrust transmitted in the rocks near the surface than through those near the zone of flow for two reasons, because the rocks are more nearly rigid, transmitting a greater proportion of the forces extant, and because near the surface there is more total horizontal force to be transmitted. These conditions may be analyzed as an unequally distributed force of the rotational type. Since the strain is greatest where relief of pressure is easiest, it follows that the strain is greater near the surface than at depth, which would result in a rotational strain even if the forces were translatory.[1] Thus rotational strain results from a ready relief of pressure near the surface, and it appears reasonable that the original stresses applied also are rotational.

The length of the crustal members.—The commonly deformable crust is considered to be a discontinuous structure in the form of a supported hollow sphere composed of irregularly shaped, curved strata plates which are geographically coincident with the continental and oceanic segments. These members of the structure exert thrust forces on one another which are localized in their maximum application at the planes of contact, i.e., the borderland of continents and oceans. Roughly speaking, the members involved in the compression are as long as the continents and ocean basins are wide. The forces, however, are not of equal intensity everywhere along the length of each member; under normal conditions they are least in the center and greatest at the ends. If the earth's crust were truly rigid the intensity of thrust would be equal throughout the length of each member, each segment would serve as a footing for its neighboring segments, resulting in failure of the segments near their centers. Apparently the

[1] F. D. Adams and J. A. Bancroft, *Jour. Geol.*, XXV (1917), 637; R. T. Chamberlin and W. Z. Miller, *ibid.*, XXVI (1918), 35–37.

members fail near their ends probably due to the fact that forces are not transmitted well through partly deformable members. The condition of a single member may be represented as in Figure 1, in which it is indicated that the thrust decreases from a maximum at the edges of the continental and oceanic segments to a minimum near their centers. Part of the force is absorbed in minor deformation of the member and only part is transmitted; therefore, the increase of force toward the end of the members is not one of arithmetical progression. Thus the yielding of the earth's crust permits the stresses relief, so that at one time the intensity of

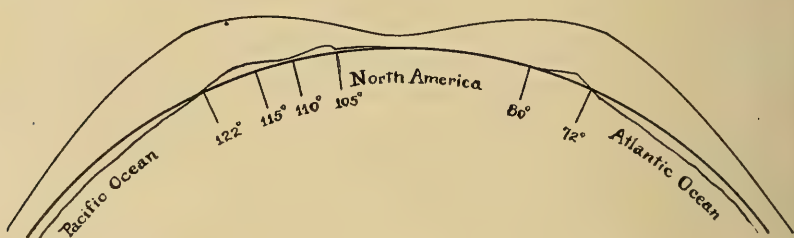

FIG. 1.—Diagram to illustrate the supposed distribution of transmitted crustal stresses. The top line is supposed to represent graphically the magnitude of the transmitted stresses. The transmitted stresses vary from a minimum near the centers of the oceanic and continental segments to zones of maximum intensity near the borders of the continents.

thrust on one side of a yielding section is much greater than the intensity of thrust on the other side of the yielding section. This condition results in a movement of part of the member in the direction of the lower intensity of thrust. This direction of movement is commonly said to be the direction of the deforming force. However, action and reaction being equal and opposite, the direction of any force must be two-faced. But whatever the direction of movement, either toward or from the continental masses, the continental masses exert just as great a thrust upon the oceanic masses as they bear themselves. Consequently there must be a tendency for the oceanic masses to suffer deformation, especially near the continents. There is supposed to be a region or band of great stress at the borders both of oceanic and continental masses, within which major deformation should be expected.

Let it be noted, however, that this band of great stress is supposed to be but a part of the total member under compression.

The depth of the crustal members.—According to Chamberlin and Salisbury[1] (writing in 1904) the average thickness of the folded shell is probably between three and five miles. From the context it appears that the estimate was based, in part at least, upon a reconnaissance report on the amount of uplift and shortening involved in the Appalachian folding, and the resulting figure probably should be modified especially by the results of R. T. Chamberlin before quoted, as well as by the many contributions based upon experiments made since 1904. Heim concludes from his studies in the Alps that there the great deformations were relatively shallow in extent. In 1912 F. D. Adams reported that open cavities might persist in rocks at depths of at least eleven miles,[2] from which it appears that the zone subject to fracture and flow, or plastico-frangible deformation, might be deeper than usually expected. But from his work in association with Bancroft,[3] Adams finds that the amount of thrust required to produce deformation increases rapidly with the increase in depth, and therefore concludes that the transference of material at the earth's crust must take place comparatively near the surface. Bridgman,[4] who subjected metal pieces to pressures comparable to those that are supposed to obtain at depths of between twenty and seventy miles, agrees that substances tend to become more rigid under high pressures, but reports further that under great pressures there is no relation between the yield and rupture points, for there is no rupture point. Materials (metals at least) deform without rupture, although they remain highly rigid. This is the condition supposed to be characteristic of the great interior of the earth, which is therefore called plastico-rigid.[5]

[1] *Op. cit.*, p. 126; cf. Bailey Willis, *U.S. Geol. Surv.*, *13th Ann. Rept.*, Part II (1891–92), p. 228.

[2] F. D. Adams, *Jour. Geol.*, XX (1912), 97–118.

[3] Frank D. Adams and Austin J. Bancroft, *ibid.*, XXV (1917), 635.

[4] P. W. Bridgman, *Phil. Mag.* (July 1912), p. 65; see also *Phys. Review*, XXXIV (1912), 1–24.

[5] A later paper by Bridgman has further bearing on the probable plastico-rigid behavior of the interior, "On the Effect of General Mechanical Stress on the Temperature of Transition of Two Phases, with a Discussion of Plasticity," *Phys. Review*, New Series, VII (1916), 215–23. See also Joseph Barrell, *op. cit.*, pp. 431–32.

All these researches seem to indicate that the zone of fracture, folding, and of deformation in general which may be called plastico-frangible is probably confined to depths which properly may be called shallow.

T. Mellard Reade[1] used the terms sheet or strata-plate to describe the deformable parts of the earth's crust, and Chamberlin and Miller[2] suggest that the deformation of some folded mountain chains is perhaps analogous to the deformation of a thin prism or wall.

Probably few geologists would maintain that the frangible part of the earth's crust is more than fifteen miles deep.

The probability of crustal members as such.—Thus, the crustal members are conceived to be sheets conforming to the curvature of the earth, from 200 to 300 times as wide and long as they are thick. Their proportions may be compared to those of a pavement one foot thick covering a city block about three hundred feet square. This conception of strata-plate members of great length and width might appear unreasonable were it not for the fact that each member is not an unsupported arch. Each member is very appreciably stiffened by the support of the plastico-rigid or elastico-rigid mass beneath.

A consideration of the probable effects of the yielding of such members is interesting. Supposing that there should be mountain folding near the border of a continent, the yielding decreases the stresses at the place of failure and throughout a certain distance on either side. Were the crust rigid instead of plastico-frangible, the stresses would be relieved throughout the whole of the neighboring sections, and the stress relief would be distributed promptly throughout all the members of the earth's crust. Thus, distribution of relief would tend to become world-wide, but the plastic-like behavior of the members retards such a distribution of stress and in some cases absorbs it within a relatively short distance. In such cases conditions for the continental mass may include a relieved, small, residual stress on one side of the continent and a large, almost unrelieved stress on the other side of the continent. This may result in a later break on the unrelieved

[1] T. Mellard Reade, *The Evolution of Earth Structure* (1903), p. 134.

[2] *Op. cit.*, p. 21.

side of the continent or may give rise to further slow adjustments affecting the major part of the continental member. In short, the mutual bearing of the crustal members upon one another may be partly responsible for the usual, very widespread epirogenic movements which follow mountain folding. These conceptions may appear at first glance to be clearly reactionary and out of accordance with modern views based on the research and studies of the last twenty years, especially with the conceptions of T. C. Chamberlin,[1] who discusses deep, rigid earth cones separated from one another by shear zones, but so far as is known to the writer these ideas are not necessarily in conflict with such conceptions of the earth's interior. It should be emphasized that the writer's suggestions are based on the assumption, which seems to be widely accepted, that there is a crustal member, subject to fracture and flow, separated from the underlying plastico-rigid interior by a zone of shearing or flow. The recognition of this zone of separation causing the crust and the inner mass at certain times to be a discontinuous member, the parts of which are subject to separate analysis, is absolutely fundamental to this discussion. It may be that this zone of shearing is merely an occasional phenomenon coming into being only as the result of more fundamental processes, and that its depth (and in consequence its competence) may vary from time to time with different periods of stress, and it is likely that the development of such a zone to an extent comparable with the width of a continent is an extreme and unusual condition. And it must be recognized that the writer advances this study as a contribution to the analysis of low-angle faulting, in its proper relation to the other factors listed by Chamberlin and Miller[2] in the résumé of their paper previously quoted, with this difference, arising largely from the different manner of approach, that the writer would not list "length of deformed area with respect to its other dimensions (after analogy of long column)" among the minor factors, but rather among the major factors in low-angle faulting. Nevertheless, it is held to be but one of several major factors. The revision

[1] *The Origin of the Earth* (1916), chap. viii, and *Jour. Geol.*, XXVI (1918), 197.

[2] *Jour. Geol.*, XXVI (1918), 44.

of the proportions of the crustal units, the abandonment of any idea of those members being unsupported arches, the recognition that they are probably relatively temporary phenomena coming into being only upon occasion, and the limitation of this discussion to those members subject to fracture put this conception of strata-plate members in an entirely different class from the old theory of crustal members which Chamberlin and Salisbury[1] emphatically discarded long ago.

A comparison of the crustal members with sheets and long columns. —Euler's formula[2] has been used in comparing the deformation of sheetlike members of the earth's crust to the yielding and failure of long columns because the failure of sheets is similar to that of long columns and because analyses of the deformation of sheets under lateral thrust are rare or wanting. Euler's formula applies strictly only to columns having lengths many times greater than their least diameter. Of course this formula is used merely as an illustration of the order of magnitude of the strength of a sheet. It is not accurate to apply it even to every long column; yet it applies with appropriate empirical modifications to all long columns.

W. H. Burr[3] says: "Pieces of material subjected to compression are divided into two general classes—'short blocks' and 'long columns'; the first of these only, afford phenomena of pure compression. A 'short column' is such a piece of material, that if it be subjected to compressive load it will fail by pure compression. On the other hand, a long column (as has been indicated in Art. 25) fails by combined compression and bending. . . . . The length of a short block is usually about three times its least lateral dimension."

Therefore it is concluded that the earth's crust in major deformation follows closely the behavior of long columns because it

[1] T. C. Chamberlin and R. D. Salisbury, *Geology*, I (1904), 554–62.

[2] T. T. Quirke, *Geol. Survey, Canada, Mem. No. 102*, "Espanola District, Ontario" (1917), p. 71, and Chamberlin and Miller, *op. cit.*, p. 19. According to Euler's formula the strength of a column equals

$$EI\frac{\pi^2}{L^2},$$

in which E equals the coefficient of elasticity of the material involved, I equals the moment of inertia, and L equals the length of the column.

[3] W. H. Burr, *The Elasticity and Resistance of the Materials of Engineering* (1890), p. 371.

appears to yield first by flexure and then by rupture, and that many experiments performed by Willis, Cadell, Chamberlin, Miller, and others, technically speaking, are experiments with long columns rather than with short blocks, because the members flexed before rupturing. More strictly speaking, most of these experiments on deformable materials fall under the mechanical analyses of neither short blocks nor of long columns because of the nature of the material, but they seem to accord the more closely to long-column analysis. If an adequate amount of experimental and analytical work had been done upon the deformation of sheets,[1] the writer would have used only the sheet as an illustration of earth deformation.

THE RUPTURE OF SHEETS AND LONG COLUMNS

Experiments with sheets under rotational stress.—In hope of learning more about the deformation and rupture of sheets the writer performed a few simple experiments upon easily controlled members. T. Mellard Reade has done sufficient work with straight and circumferential compression upon sheets, but the effects of a vertically unequally distributed stress heretofore have not been tried. Reade[2] draws conclusions from the deformation of the lead lining of a scullery sink. The writer used a common bench vise to deform and rupture plates of soap and paraffin. Of the two, soap was the more satisfactory. In order to secure an unequally distributed stress a wedge was inserted, large end upward, between the end of the member and the face of the vise. This resulted in bringing greater pressure to bear near the top than near the bottom of the plate. If the plate had been quite free to bend it would have bent downward; however, that would not have illustrated the deformation of rock strata, and the member was therefore stiffened enough by slight pressure from below to make it bend upward. After the bending of the soap, rupture started from the bottom at a low angle from a point nearly equidistant from each

[1] The only work known to the writer which appears to have a bearing on the subject is "Tests of Reinforced Concrete Flat Slab Structures," by Arthur N. Talbot and Willis A. Slater, *University of Illinois Bull.*, Vol. XIII, No. 22, 1916.

[2] T. Mellard Reade, *The Origin of Mountain Ranges* (1886), pp. 15–16, and Plate VI, p. 28.

side, became nearly horizontal near the center, and increased to nearly 60° as it approached the upper surface (Fig. 2). To prove that this is the usual type of break and not fortuitous, two more pieces of soap were flexed and broken with similar results. Two narrow pieces of soap broke with nearly vertical shear planes near

FIG. 2.—(*a*) A sheet of soap ruptured by combined compression and bending under rotational stress. The fault plane is high-angled near the surface and low-angled below the center of the member. These pieces are outlined in Figure 3. (*b*) A sheet of paraffin ruptured by combined compression and bending under rotational stress. The fault plane is almost horizontal for most of the length, changing sharply at a high angle to the surface. At one end the member is split down the center along the plane of maximum shear without actual breaking out of the piece; see also Figure 5, (*a*) and (*b*).

the edges (Figs. 2 and 3), but a plate wider than it is long ruptured without vertical shear planes at a low angle (Fig. 4). It seems that nearly vertical fault planes may be disregarded, occurring merely because the sheets are narrow and have lateral relief. In the case of earth deformations in general, the width of the sheet or strata-plate is probably comparable to the length of the defor-

mation member, and vertical fault planes of a comparable origin are not commonly recognized.

Experiments with short blocks under rotational stress.—Experiments with paraffin led to somewhat different results. The

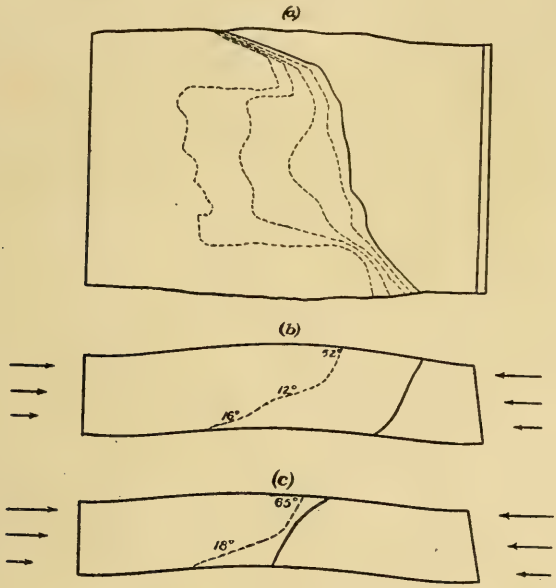

FIG. 3.—(*a*) and (*b*) are two views of a sheet of soap which failed by combined compression and bending under rotational stress. The dimensions of the piece of soap are $\frac{8}{10}\times 4\frac{1}{2}\times 2\frac{1}{2}$ inches. The contour intervals are $\frac{2}{10}$ inch, indicating the plane of rupture. A photograph of the piece is reproduced in Figure 2. (*c*) is a cross-section of another piece of soap showing a similar rupture. The dimensions are $\frac{7}{10}\times 4\frac{2}{10}\times 2\frac{2}{10}$ inches.

paraffin members did not flex so readily as soap, and therefore, in spite of their dimensions, they approach the behavior of short blocks under the conditions of these experiments. The members did not break from the bottom to top but after a few preliminary high-angle slice faults part of the members seemed to chip out (Fig. 5, *c* and *d*), illustrating the manner in which weak unbending blocks yield under a rotational compression.[1] However, having

[1] In experimental engineering any cement block which is loaded with an unequally distributed load fails by breaks, making low angles with the direction of applied force. Such breaks are considered faulty, because the object of that work is to determine the strength of the blocks under equally distributed stress.

flexed slightly, one paraffin member started to split down the center along a plane parallel to the surface in the manner of a bending column (Figs. 5 and 2).

Chamberlin and Miller[1] had obtained similar low-angle breaks when they caused rotational strain in a paraffin short block, thereby proving their contention in favor of the importance of rotational strain as a cause of low-angle faulting. The writer

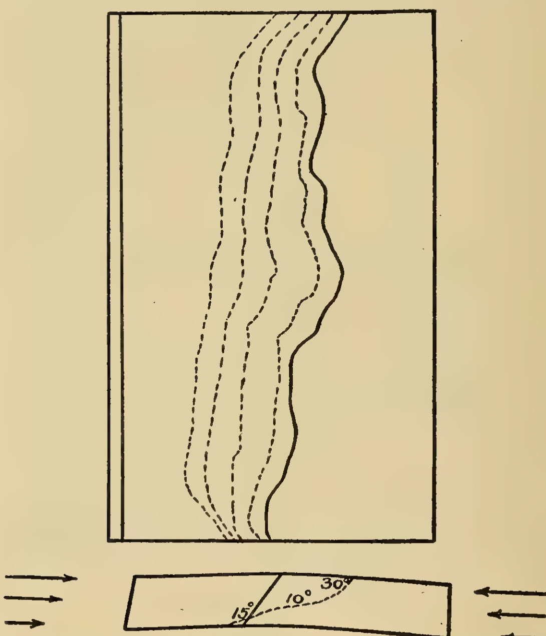

FIG. 4.—A wide sheet of soap which failed under rotational stress by combined compression and bending. The dimensions of this piece are $2\frac{4}{10}\times4\times\frac{4}{10}$ inches and the contour lines are equidistant. They indicate the place of rupture.

has used a rotational stress and bending sheets rather than short blocks in order to be consistent in the general treatment and object of the paper and for the sake of the mechanical considerations which are treated later.

Analysis of the rupture of sheets and columns under translatory forces.—Long columns and sheets fail by bending and by rupture

[1] *Jour. Geol.*, XXVI (1918), 35, and Fig. 16.

under continued compression. A column may crumple into many folds or it may spring out into a single arch. The second case is stable for unsupported columns, but in the case of the earth's crust the formation of many folds is common. Mechanically the analysis of the stresses in one fold of a series is the same as that in a single arch. The maximum tensional stress is at the apex of the

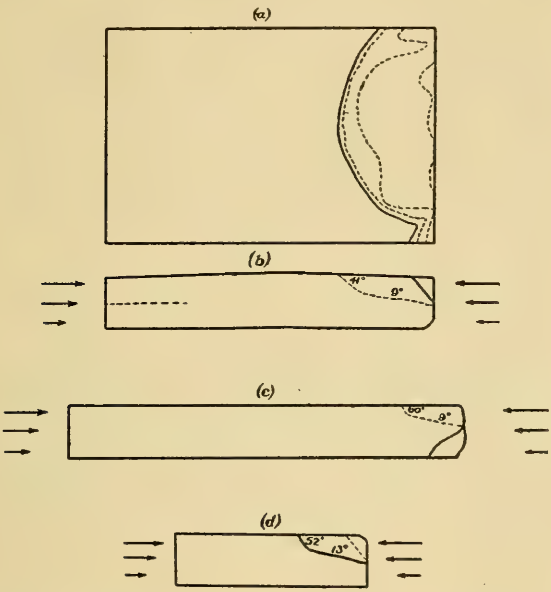

FIG. 5.—Paraffin members which failed under rotational stress. (*a*) and (*b*) are two views of a piece $\frac{6}{10}\times3\frac{8}{10}\times2\frac{4}{10}$ inches in size, which yielded by combined compression and bending. Compare Figure 2 and note the place of rupture along the plane of maximum shear parallel to the surface. (*c*) is a side view of a piece $\frac{6}{10}\times4\frac{6}{10}\times2\frac{4}{10}$ inches which seemed to fail by mere compression; the break indicated by dotted lines followed several high-angle breaks. (*d*) is a side view of a piece $\frac{6}{10}\times2\frac{3}{10}\times2\frac{4}{10}$ inches in size which ruptured without flexing. Note the tendency toward high-angle breaks.

arch at the surface, the maximum compression beneath the apex of the arch at the bottom of the deformed member, the focus of maximum shear a plane containing the axis of the member and parallel to the plane of greatest length and width of the member (Fig. 6*B*, *S–S*). A bending member which yields to shear alone splits from end to end along a plane of maximum shear, a similar

member yielding to tension parts in a plane at right angles to its axis. Figure 7 illustrates the rupture of flexed wooden columns by tension and shear. Examples *A* and *B* have ruptured by tension and by shear, whereas example *C* has ruptured by a combination of tension and shear. Applying these illustrations to conditions in the earth's crust, it is probable that rock is so weak to resist tension that under continued straight compression its folds are likely to rupture at the arches by tension. In the case

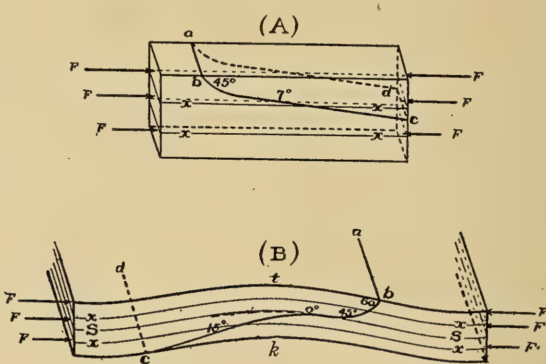

FIG. 6.—*A* illustrates the character of rupture of a short block under highly rotational compression. The surface *abcd* represents the break. The planes marked *x* represent the distributed shear due to the unequally distributed forces *F*. *B* illustrates the character of rupture of a long column or of a flexible sheet by rotational compression. The plane marked *S* is the plane of maximum shear due to flexure; the planes marked *x* indicate the planes of distributed shear and the action of the unequally distributed forces *F*. The place of maximum tension is marked *t* and the place of maximum compression is marked *k*. The rupture *abcd* ideally follows the plane *S–S* partly and emerges near *t*.

of major terrestrial deformations, however, straight compression is thought to give place to rotational forces, and the situation is changed.

Analysis of the rupture of sheets and columns under rotational forces.—Any compressive force unequally distributed in its application gives rise to shearing stresses within the member affected. The case of members folded by rotational forces includes tension due to bending, shear due to bending, and shear due to rotational stress. The plane of maximum shear is somewhere near the middle

of the member (Fig. 6), and the tendency to shear due to rotational stress is distributed in parallel planes, one of which must coincide with the plane of maximum shear due to folding. Thus rotational stress adds a tendency to shear along the plane of maximum shear already developed by folding. This explains the low-angle breaks

FIG. 7.—The rupture of flexed wooden columns by tension and shear. Under flexure, columns tend to split from end to end due to shearing, and to part in a plane at right angles to their long axes above the plane of shear by tension. Tension is greatest at the top of the arch, and shear is greatest along the center of the member. *A* and *B* show separate breaks due to shear and tension and *C* shows rupture induced by a combination of shear and tension.

near the center of the slightly flexed paraffin sheet (Figs. 2 and 5), and the suggestion of a very low-angle break near the center of the ruptured soap (Figs. 2 and 4).

Contemporaneous with this tendency to shear along a plane parallel to the axis of the deformed member, there is a lesser tendency to rupture by tension. The tensional break approaches a plane normal to the top of the arch, at right angles to the plane of maximum shear (Figs. 6 and 7*A* and *B*). A combination of these two is a plane which sweeps through a considerable change of

position amounting to 90° in extreme cases. Such a combination is illustrated in the breaking of one wooden piece (Fig. 7*C*) and in the rupture of the soap and paraffin (Figs. 2, 3, 4, and 5).

Comparisons between geological thrust deformations and members ruptured by rotational stress.—In cases where rock members are subjected to both tension and shear we expect failure to be due to that which the rock is least able to withstand, that is, a combination of both shear and tension. Rocks are strong to resist compression, and failure of rock members by straight compression needs little consideration when either great shear or great tension is involved.

Comparisons between the rupture of these members which fail by combined compression and bending, the rupture of short blocks which fail by pure compression, and the geological relations of overthrust and reverse faults seem to suggest that many thrust faults may have resulted from the yielding of flexed members which have failed along planes of shear and tension, members of the class of long columns.

Thus it appears that some members under terrestrial compression are curved sheets or strata-plates, which are thin in comparison with their width and length; being subjected to an unequally distributed rotational stress they break normally along shear planes of low angles at depths which steepen to high angles due to tension near the surface.

KINETICS OF THRUST FAULTING

Analysis of the conditions following rupture and preceding displacement.—Some rotational force deforms the terrain by flexure. If the folding is sharp no fold can transmit thrust because the fold must fail at the crown of the arch due to localized tension. Rock is incompetent to carry tensional stresses, and therefore a high arch fails under lateral compression. If the arch fails, no appreciable thrust can be transmitted until folding has reached an isoclinal condition, involving great shortening, great thickening, and thereby great strengthening of the member.[1] This case is extreme and must be rare. More commonly the folds are so low that thrust

[1] Cf. Quirke, *op. cit.*, p. 72.

can be transmitted without rupture of the arches, and rupture follows the forms outlined above (Fig. 6). In an analysis of the conditions at the instant after rupture, let P be the total compressive force, let G be the weight of the moving mass, let Θ be the angle of shearing at any one place, and let a represent the cross-sectional area of the member. Then, as Chamberlin and Miller show,[1] the intensity of thrust (p_t) tangential to the shear plane is

$$p_t = \frac{P \sin\Theta \cos\Theta}{a}$$

and the intensity of the normal stress (p_n) is

$$p_n = \frac{P \sin^2\Theta}{a}$$

Likewise, the force of gravity is resolved into tangential and normal components, the tangential opposing the tangential component of the thrust, and the normal being added to the normal component of the thrust. The tangential component of gravity is

$$G_t = G\, x \sin\Theta\,,$$

and the normal component is

$$G_n = G\, x \cos\Theta\,.$$

The intensity of the tangential component of gravity is

$$g_t = \frac{G \sin\Theta}{a \cot\Theta} = \frac{G}{a} \sin\Theta \tan\Theta\,.$$

The intensity of the normal component of gravity is

$$g_n = \frac{G \cos\Theta}{a \cot\Theta} = \frac{G}{a} \sin\Theta\,.$$

Thus, after rupture the intensity of thrust becomes

$$\frac{P \sin\Theta \cos\Theta}{a} - \frac{G \sin\Theta \tan\Theta}{a} = \frac{\sin\Theta}{a}\,(P \cos\Theta - G \tan\Theta),$$

and the intensity of friction becomes

$$\mu\left(\frac{P \sin^2\Theta}{a} + \frac{G}{a} \sin\Theta\right) = \mu \frac{\sin\Theta}{a}(P \sin\Theta + G)\,,$$

in which μ represents the coefficient of kinetic friction.

[1] *Jour. Geol.*, XXVI (1918), 15 ff.

In order to achieve displacement,

$$\frac{P \sin \Theta \cos \Theta}{a}$$

must be sufficiently greater than

$$\frac{G \sin \Theta \tan \Theta}{a}$$

to overcome the friction due to both the normal component of thrust and the normal component of gravity. The friction will become less per square unit of fault plane as slickensides and other smooth surfaces are developed by movement. But the total area of friction increases with displacement, and it follows from the preceding formulas that friction is greatest in intensity where Θ, the angle of displacement, is greatest.

The fault plane decreases in steepness as displacement increases.—Rupture being accomplished, as indicated in Figure 6*B*, the fault plane varies from places of low dip far beneath the surface to places of high dip nearer the surface. Where the angle is low the tangential thrust is greatest, the normal component of thrust is least, but the normal component of gravity is a maximum, and the resistant, tangential component of gravity is a minimum. Near the surface where the angles are high and the normal component of gravity is low, the resistant tangential thrust due to gravity is a maximum and the tangential component of the compressive force is a minimum, but its frictional component is a maximum. In all these movements the compressive thrusts must be dominant, otherwise the force of gravity and friction would prevent displacement. Therefore, displacement being granted, the effect of gravity is not vital in the discussion. Obviously, then, the effects of thrust result in a maximum shear along low-angled planes and a maximum friction at high-angled planes.

In the general case of rupture represented in Figure 6*B* maximum friction is near the surface. The hanging wall of millions of tons of rock moving several miles along this fault plane will result in enormous abrasion, much as a glacier abrades greatly the stoss sides of steep opposing hillsides, and this abrasion will be greatest

where friction is greatest, at the steepest part of the plane, affecting both the footwall and the hanging wall. During early displacement the fault will appear at the surface as a steeply dipping plane; by the time displacement has continued for a mile, the angle of the fault plane must have been worn flatter by the friction of the moving load; finally, by the time displacement has attained a few miles, the low-angled sole will have reached the surface, and the fault plane must have been reduced to a low angle by abrasion, leaving no trace of the steep parts of the original break.

In this manner it is suggested that all great thrust faults which are steep-angled near the surface, if persistent in depth, follow the low-angle form at the depth of a few miles, and that in a general case the angle of faulting at the surface may depend as much upon the amount of displacement subsequent to rupture as upon fundamentally different conditions in the application of earth forces or in the character of the members affected. In support of this it may be recalled that, so far as is known regarding thrust faults, all faults of great displacement have low-angle fault planes, and no faults of high angles exceed a few miles in displacement.

Willis[1] has described rotated, high-angle thrust faults of relatively small throw in the coast ranges and the Sierra Nevada, which he considers to have some such shape as is here suggested for thrust faults of small displacement; however, his explanation of their character differs considerably from the general argument of this paper.

CONCLUSION

In conclusion some repetitions seem pertinent. Certain parts of the earth's crust which are deformed by regional compression are held to be analogous to sheets and comparable in mechanical analysis to long columns. The normal terrestrial stress is said to be an unequally distributed thrust of rotational type. The transmission of stress as a vector quantity supposedly extends from the surface to a depth scarcely exceeding fifteen miles. There is a zone of potential separation between the frangible crust and the rigid interior which is nearly parallel to the surface. In some cases thrust faults of very great displacement may be extensions

[1] Bailey Willis, *Geol. Soc. Amer. Bull.*, XXX (1919), 84–86.

of this low-angle zone of parting to the surface at an increasing degree of steepness;[1] in other cases rupture occurs within the bending part of the crust near the plane of maximum shear with a break low-angled at depth and increasing in steepness near the surface. In either case displacement of less than one mile results in a steep-angle fault, an ordinary reverse fault, but displacement of several miles results in reduction of steepness of the fault plane by the abrasion of the footwall and by advancement of the low-angle part of the hanging wall to the surface. Thus some low-angle overthrust faults and high-angle reverse faults may represent different stages of a single process.

[1] T. C. Chamberlin, *Econ. Geol.*, II (1907), 597–99.

PLEISTOCENE MOLLUSCA FROM INDIANA AND OHIO[1]

FRANK COLLINS BAKER
Curator, Museum of Natural History, University of Illinois

Two very interesting and valuable collections of Pleistocene material have recently been placed in the hands of the writer for study. These contain a number of species not previously reported from fossiliferous beds, which add largely to our knowledge of the distribution of this group of animals during the great Ice Age. These deposits will be discussed separately and their biotic content compared.

I am indebted to Dr. Morris M. Leighton, of the department of geology, University of Illinois, for the opportunity of studying the Ohio deposit, and to Rev. W. H. Fluck, of Hope, Indiana, for the material from the Indiana deposit. The following gentlemen have examined critical material and to them my thanks are due: Dr. H. A. Pilsbry, Academy of Natural Sciences, Philadelphia, Amnicolidae; Dr. V. Sterki, New Philadelphia, Ohio, Sphaeriidae; Dr. Bryant Walker, Detroit, Michigan, Amnicolidae and Physa; and Mr. Calvin Goodrich, Pleuroceridae.

THE OHIO DEPOSIT

The material from Ohio occurs in extensive marl beds at the south end of Rush Lake, Logan County. Dr. M. M. Leighton, who collected the material, thus describes the deposit:

> The exposure occurs in an artificial ditch which drains into the lake from the south. The beds begin close to the lake and run south for a hundred yards or more. The farm land immediately to the east shows great numbers of these shells mixed in with the soil. The exposure is about six feet deep, and the shells make up whole beds of lenticular shape, interbedded with clay strata, in some of which are a few scattered shells. Some of the shell beds are as much as ten inches thick. The interbedded clay shows no lamination and is dark in color. I do not believe there is any question about their being post-Wisconsin in age, but on the other hand they do not seem to be extremely recent.

[1] *Contribution from the Museum of Natural History,* University of Illinois, No. 9.

Logan County is within the late Wisconsin drift border and the fauna is without question of post-Wisconsin age.

The fauna of the Ohio deposit contains several species of unusual interest. A new variety of *Amnicola* is related to a recent species described from Maine—*Amnicola winkleyi leightoni.* The two forms are widely separated geographically, but the relationship seems unquestionable. It is probable that this variety, as well as the typical form, occur in other places between the two localities, but have not yet been recognized. All of the large Amnicolas have generally been identified as "*limosa*" and many of the more recently described species and races of this and other groups will be found in other Pleistocene deposits when these are critically examined. *Physa anatina* is the most easterly record for this species which is abundant, living, west of the Mississippi River, and also more or less common in Illinois and Michigan. This is the first record of this *Physa* in Pleistocene deposits of the glaciated regions. The recently described *Planorbis altissimus*, first noted in a marl deposit in Illinois, occurs in abundance in the Ohio deposit. This small *Planorbis* is believed to have a wide distribution in the eastern and central parts of the United States in Pleistocene formations. It may also occur living. The number of species and varieties of the genera *Valvata, Amnicola,* and *Planorbis* in this deposit is also noteworthy.

It will be observed that in the Ohio deposit there are no land shells and only one naiad species, an *Anodonta*, a genus characteristic of quiet bodies of water like lakes and ponds. The *Sphaerium* is a species commonly found in lakes. The other genera present, particularly *Valvata* and *Planorbis*, contain species that usually have a wide distribution in lakes. The Ohio deposit may, therefore, be considered as having lived in a larger Rush Lake, perhaps not long after the ice had disappeared from Ohio.

The Indiana deposit contains many land shells and six species of naiads, characteristic of rivers and streams. *Sphaerium* and *Pisidium* are largely represented, as is also the family Amnicolidae. The presence of *Goniobasis semicarinata* also stamps this deposit as fluviatile in character, as distinguished from the Ohio deposit,

which is lacustrine. The family relationship as regards number of species represented in the two deposits is shown in Table I.

TABLE I

COMPARISON OF FAMILIES IN OHIO AND INDIANA DEPOSITS

	Ohio Lake Deposit	Indiana River Deposit
Unionidae	1	6
Sphaeriidae	8	12
Valvatidae	4	1
Amnicolidae	3	7
Pleuroceridae	....	1
Viviparidae	....	1
Ancylidae	1	1
Physidae	1	1
Planorbidae	7	2
Lymnaeidae	2	1
Total number of species	27	33

The species of the two deposits are shown in Table II, in which the particular species in each family are listed. It will be noted that there are twenty-seven species and races in the Ohio deposit and thirty-three species and races in the Indiana deposit.

TABLE II

COMPARISON OF FOSSIL FAUNAS

Ohio	Indiana
....	*Lampsilis ventricosa*
....	*Amblema undulata*
....	*Carunculina glans*
....	*Elliptio crassidens*
....	*Elliptio gibbosus*
....	*Actinonaias ellipsiformis*
Anodonta species	....
....	*Sphaerium solidulum*
....	*Sphaerium stamineum*
....	*Sphaerium striatinum*
....	*Sphaerium fabale*
Sphaerium sulcatum	....
Musculium rosaceum	....
....	*Pisidium virginicum*

TABLE II—*Continued*

COMPARISON OF FOSSIL FAUNAS

Ohio	Indiana
Pisidium compressum, var.	*Pisidium compressum*
....	*Pisidium cruciatum*
....	*Pisidium kirklandi*
....	*Pisidium fallax*
Pisidium pauperculum	*Pisidium pauperculum*
Pisidium noveboracense	*Pisidium noveboracense*
....	*Pisidium abditum*
Pisidium variabile	....
Pisidium tenuissimum	....
Pisidium medianum	....
Valvata tricarinata	*Valvata tricarinata*
Valvata tricarinata perconfusa	....
Valvata tricarinata unicarinata	....
Valvata sincera	....
Amnicola walkeri	*Amnicola walkeri*
Amnicola lustrica, var.	....
....	*Amnicola lustrica*
....	*Amnicola limosa parva*
Amnicola winkleyi leightoni	....
....	*Pyrgulopsis sheldoni*
....	*Somatogyrus depressus*
....	*Pomatiopsis lapidaria*
....	*Pomatiopsis cincinnatiensis*
....	*Goniobasis semicarinata*
....	*Campeloma integrum obesum*
Ferrissia parallela	....
....	*Ferrissia rivularis*
Physa anatina	....
....	*Physa crandalli*
Planorbis campanulatus	....
Planorbis antrosus	*Planorbis antrosus*
Planorbis antrosus striatus	....
Planorbis altissimus	....
....	*Planorbis parvus*
Planorbis deflectus	....
Planorbis hirsutus	....
Planorbis exacuous	....
Galba palustris	....
Galba obrussa decampi	....
....	*Galba humilis modicella*

THE INDIANA DEPOSIT

The material from Indiana is from Flat Rock River, German Township, Bartholomew County. The deposit was discovered and has been studied quite extensively by Rev. W. H. Fluck, of Hope, Indiana, to whom I am indebted for the opportunity of working up this very interesting lot of mollusks.

Mr. Fluck writes as follows of the deposit and the territory immediately surrounding this place:

> On the surface, everywhere, we have glacial deposits in the form of clay, sand, gravel, and loam. The Illinoian moraine and the Shelbyville moraine are both south of these shell deposits. To the north are other moraines. In fact, the Flat Rock River flows a part of its course between moraines, to the north and east of the "Bartholomew Deposits," as I call the shell place. The top stratum, a sandy loam, in which the shells are found, is from two to twelve or more feet deep. Below this there is good gravel and sand. The river banks are twelve to fifteen feet high. On the east side of the river there is an open gravel bed where I also took shells. The shells range from just beneath the soil to as far down as I could examine, that is, down to the river surface, and, I suspect, down to the Devonian rock, over which the glacial deposits now lie. To be clear, on the east and west side of the river, and all along for several miles, below the Wisconsin drift, the shells are found. I have not explored north of this. On the west side, the shells come from a steep bank in which the shells are imbedded at all depths. On the east side, at about twenty-five yards back from the bank, I took some from an open gravel bed, not out of the gravel, but from the sandy loam above the gravel. The sample of soil and shells I am sending you came from the west bank, at about twelve feet below the surface.

The shells in the deposit seem referable to the Sangamon interglacial interval. The deposits of sand, sandy loam, and gravel are in valleys that were used as lines of drainage from the early and late Wisconsin ice sheets (see Leverett, 1902, Pl. II). The Illinoian till is only four or five miles west of Flat Rock River and the material in the stream valleys appears to be outwash or drainage material from the later ice sheets. Of the Sangamon interval in Indiana, Leverett says:

> The Sangamon soil and weathered zone may be seen beneath the surface silt in thousands of exposures in southeastern Indiana and southwestern Ohio, for the general thickness of the soil is only four or five feet. Farther north

there are, in addition to the silt, the heavy deposits of Wisconsin drift, which have buried the soil and weathered zone to such a depth that it is rarely exposed. However, a few exposures have been found in the deeper valleys, and wells not infrequently penetrate both the silt and soil under the Wisconsin drift (1902, p. 292).

On another page the same author says:

In fact, the great majority of buried soils reported in Ohio, Indiana, and Illinois appear to be at this horizon (p. 293).

The shells in the deposit under discussion are not from one of these old soil horizons. They represent, probably, material that was washed down from flood plains farther upstream, where they had been deposited during periods of flood previous to the advance of the Wisconsin ice cap. The fact that the shells are found from just beneath the surface to the lowest strata accessible, as described by Mr. Fluck, indicates that the burying of the shells occurred more or less continuously during the deposition of the valley deposit.

What relation the Peorian interval may bear to these shells is not at present known, the Iowan invasion apparently not notably affecting this territory so far east of the area of this drift. The mollusks might have lived during Peorian time and then been buried by the Wisconsin deposits. As the land fauna is so nearly like that of deposits farther south, which are referred to the Sangamon interval by Leverett, it seems best to refer the Flat Rock shells to the same horizon. At Lawrenceburg, near the Ohio-Indiana line, old soils (forest beds) containing shells are found. Some years ago Mr. A. C. Billups (1902, p. 50) listed many species of land mollusks from the deposits along the Ohio River near Lawrenceburg. These are listed in Table III for comparison with the Flat Rock shells, which are also shown in this table. It will be noted that the two faunas are substantially the same. The difference is only what we would find in comparing the recent faunas of two more or less widely separated areas. It would appear, therefore, that the reference of the Flat Rock River shells to the Sangamon interval is well supported by the geological as well as faunal evidences.

Many deposits in the valleys of streams that formed drainage channels from the Wisconsin ice sheets probably contain the remains

of faunas belonging to the Sangamon or Peorian intervals, and the study of this material from a wide area would aid very largely in understanding the interglacial and postglacial migrations of many

TABLE III

LAND SHELLS OF TWO INDIANA DEPOSITS

Lawrenceburg	Flat Rock River
Vallonia pulchella	....
Cochlicopa lubrica	....
Gastrocopta contracta	*Gastrocopta contracta*
Gastrocopta armifera	....
Pupoides marginatus	....
Succinea species	....
....	*Succinea avara vermeta*
Helicodiscus parallelus	*Helicodiscus parallelus*
Pyramidula perspectiva	....
Pyramidula cronkhitei anthonyi	....
Pyramidula solitaria	*Pyramidula solitaria*
Pyramidula alternata	*Pyramidula alternata*
Gastrodonta ligera	*Gastrodonta ligera*
Vitrea hammonis	*Vitrea hammonis*
Vitrea indentata	*Vitrea indentata*
Circinaria concava	*Circinaria concava*
Polygyra monodon	*Polygyra monodon*
Polygyra stenotrema	*Polygyra stenotrema*
Polygyra mitchelliana	....
....	*Polygyra clausa*
Polygyra thyroides	*Polygyra thyroides*
Polygyra pennsylvanica	....
Polygyra elevata	*Polygyra elevata*
Polygyra appressa	....
Polygyra palliata	*Polygyra palliata*
Polygyra multilineata	....
Polygyra zaleta	*Polygyra zaleta*
Polygyra albolabris	....
Polygyra profunda	*Polygyra profunda*
Polygyra inflecta	*Polygyra inflecta*
Polygyra tridentata	*Polygyra tridentata*
....	*Polygyra fraudulenta*

species of mollusks. A case in point is the presence of the minute fresh-water snail known as *Pyrgulopsis sheldoni* in this old interglacial deposit. This species was described from material dredged

in Lake Michigan, off Racine, Wisconsin, at a depth of thirty fathoms. Additional records from both recent and fossil faunal areas are needed to understand the distribution of this tiny species. Geologists or others who discover such deposits should carefully collect the material, noting rather minutely the stratigraphy, and send the material, unsorted, to some competent malacologist for study. Such deposits occur plentifully in Iowa, Wisconsin, Illinois, Michigan, Indiana, Ohio, and Maine, and also in parts of other states which were overridden by the great ice sheets.

The material described in this paper forms a part of the Pleistocene collection of the Museum of Natural History of the University of Illinois.

ANNOTATED LIST OF MOLLUSCA FROM THE POSTGLACIAL DEPOSITS NEAR RUSH LAKE, LOGAN COUNTY, OHIO

Unionidae

Anodonta species. Fragments of a naiad, apparently a thin-shelled *Anodonta*, occur with the material. Evidently rare, as but few fragments were found.

Sphaeriidae

Sphaerium sulcatum (Lamarck). This large *Sphaerium* is abundant in the material from the Ohio deposit and is the only member of the genus found. These shells vary in form more than do most individuals of the recent fauna.

Musculium rosaceum (Prime). A dozen odd valves of a *Musculium* are referred to this species by Dr. Sterki, who says: "*Musculium*, different forms, but apparently of *rosaceum*, deformed."

Pisidium compressum Prime. A common, almost abundant species in this marl bed, but none typical. Sterki says: "near variety *laevigatum*."

Pisidium variabile Prime. About as common as *P. compressum*. Sterki states that this species is difficult to separate from *compressum*, especially among fossil individuals. This fact would indicate a common origin for both species, and the study of the Pleistocene material is, therefore, very important from the standpoint of geological evolution.

Pisidium tenuissimum Sterki. The most abundant species of Sphaeriidae in the deposit and quite typical of the species. This *Pisidium* seems to be a common Pleistocene fossil, occurring in widely separated deposits in Maine, Michigan, Ohio, and Illinois. In the deposits at Urbana, Illinois, believed to be pre-Wisconsin, a variety of this species—*calcareum* Sterki—is the most abundant mollusk in the material examined (see Baker, 1918, p. 663). It is quite significant that *tenuissimum* has not yet been found in deposits older than post-early Wisconsin; none are recorded from Sangamon or Peorian deposits. It is absent from the Indiana deposits discussed in this paper and believed to be of Sangamon age.

Pisidium medianum Sterki. A score of Pisidia, with small, thin shells and very prominent beaks, are referred to this species by Dr. Sterki.

Pisidium noveboracense Prime. *Pisidium pauperculum* Sterki. Two valves each of the foregoing species were identified from the material by Dr. Sterki. They are both typical of the species.

Valvatidae

Valvata tricarinata (Say). This is one of the most abundant species in this marl deposit. The majority of the specimens have three strong raised keels and are in every way typical of the species. In a few forms, however, the central carina is faintly developed, showing a variation toward the next variety.

Valvata tricarinata perconfusa Walker. About 10 per cent of the carinate Valvatas belong to this variety. There is some variation in the smooth space between the carinae on the shoulder of the whorl and on the base of the shell, there being in some specimens a faint ridge indicating the position of the central carina in typical *tricarinata*.

Valvata tricarinata unicarinata DeKay. A single specimen of DeKay's variety was found among several hundred *tricarinata*. This variety appears to be rare among both fossil and recent members of the species.

Valvata sincera Say. Three specimens of this characteristic species were picked out of a quart or more of marl specimens

(about 20,000 specimens), indicating that this species is very rare in this marl deposit. Compared with the same species from the marl deposit in Urbana, Illinois, the Ohio shells are a trifle more depressed.

Amnicolidae

Amnicola walkeri Pilsbry. Most of the Amnicolas referred to this species are quite typical, agreeing with Walker's figure in the *Nautilus* (Vol. XIX, Pl. V, Fig. 12). A few individuals have a higher spire with strongly rounded whorls and a very deep suture, i.e., scalariform. The largest specimen measures about 2.5 mm. in length. This characteristic species is not common in this deposit, only about fifty specimens being found in picking over a quart of material.

Amnicola lustrica Pilsbry. Variety. "Larger, more solid, with the lip much thickened within" (Pilsbry). This *Amnicola* is, equally with the following species, the most abundant species in the deposit, nearly 40 per cent of the bulk of a quart being composed of these two species of *Amnicola*. There is some variation in the width of the shell and in the height of the spire, the whorls of which, in some individuals, are quite round, with very deep sutures. A single specimen is so decidedly scalariform as to render it quite unrecognizable without its presence in the other material. Several specimens of this variety measure 4.5 mm. in length. In most individuals the inner lip (peristome) touches the parietal wall, but in others it is separated by a deep suture and the edge of the aperture is entirely separated from the body whorl. The same form of *lustrica* occurs in post-Wisconsin deposits of the Chicago region.

Amnicola winkleyi leightoni Baker. This *Amnicola* (described in the *Nautilus*, Vol. XXXIII) is related to *winkleyi* Pilsbry, described from Saco, Maine. It is uniformly wider, with somewhat shouldered whorls. Together with *Amnicola lustrica* variety, it is the most abundant species in this deposit. That a form related to the Maine shell should be found so far removed from the original locality is surprising, particularly as it occurs in a deposit of late Pleistocene age. The specimens have been examined by Dr. Pilsbry, who indicated their relationship to his Maine species and who agreed with the author as to their distinctness as a race believed to be extinct.

Planorbidae

Planorbis campanulatus Say. A dozen specimens of this species, mostly mature, occurred in the material examined. The adults are of normal size and typical form.

Planorbis antrosus Conrad. A fairly abundant species of large-sized individuals, mostly mature. There is considerable variation among the specimens, especially in the shape of the aperture, which has a tendency to become bell-shaped. A number of individuals approach variety *aroostookensis* Pilsbry, and one specimen would certainly be called variety *portagensis* Baker, if found in Maine. Several specimens have a number of rounded ridges on the body whorl near the aperture; these indicate the location of former apertures.

Planorbis antrosus striatus Baker. About 10 per cent of the *antrosus* may be referred to this variety with strong spiral striation. This is very strongly marked in the majority of the fossils of this deposit.

Planorbis altissimus Baker. This small *Planorbis*, first described from marl deposits at Urbana, Illinois, proves to be widely distributed and to be the common *Planorbis* of the *parvus* group in the marl deposits. It is very variable, only a small percentage being typical as figured in the original description (Baker, 1918, p. 94). The aperture varies from rounded to elliptical and may be deflected to a marked degree or placed in an almost continuous line with the body whorl. In all specimens examined, however, the upper part of the aperture forms a distinct shoulder and the whorls are more or less flat-sided, features not found in true *parvus*, which is normally a smaller shell. *Altissimusis*, after *Amnicola lustrica* and *A. winkleyi leightoni*, is the most abundant shell in this deposit.

Planorbis deflectus Say. Three adult individuals of this small *Planorbis* were found in the material examined. The peripheral keel is very marked in these specimens, and the aperture varies in the degree of deflection, in one specimen being almost basal. The largest individual measures 6.5 mm. in greatest diameter.

Planorbis hirsutus Gould. A single specimen seems referable to this species, having the less conspicuous keeled periphery and rounded whorls of *hirsutus* from Massachusetts. This species seems quite separable from *deflectus*.

Planorbis exacuous Say. This flat, lens-shaped *Planorbis* is fairly common in this deposit. The specimens are of large size, several individuals measuring 6 mm. in greatest diameter.

Lymnaeidae

Galba palustris (Müller). A single broken specimen of a lymnaeid is referable to this protean species. When perfect it must have measured nearly 40 mm. in length.

Galba obrussa decampi (Streng). This small lymnaeid is quite common in the deposit. It exhibits more or less variation, principally in the degree of elevation of the spire, in the convexity of the whorls, and in the shoulder of the whorls. This species is characteristic of the cold waters of the early Wisconsin ice recession, in which it lived in considerable abundance. It is apparently much less common living in the recent fauna than it was in post-glacial or interglacial times.

Physidae

Physa anatina Lea. This large *Physa* is apparently a form of Lea's species, which occurs abundantly in the states west of the Mississippi River. It is recorded from Michigan and is said to range clear across the southern part of this state (see Walker). It is also recorded from Hardin, McHenry, and Adams counties, Illinois (see Baker, *Ill. Cat.*). There seems to be no reason why it should not be found as far east as Ohio.

The Ohio shells differ from typical *anatina* in being larger, with a wider body whorl and aperture and more flat-sided spire whorls. Adult individuals are not common in the deposit, but immature shells of four whorls are almost abundant. Variation is so great in this genus that it has not been thought best to bestow a name on this form, although it differs more or less widely from the average recent shells of *anatina*.

Ancylidae

Ferrissia parallela (Haldeman). A single specimen of this fresh-water limpet was found in the material examined. As about 20,000 shells were picked over it must be considered very rare. The specimen is typical.

ANNOTATED LIST OF MOLLUSCA FROM SANDY LOAM DEPOSITS AT FLAT ROCK RIVER, BARTHOLOMEW COUNTY, INDIANA. BELIEVED TO BE REFERABLE TO THE SANGAMON INTERGLACIAL INTERVAL

Unionidae

Amblema undulata (Barnes). Mr. Fluck reports this large naiad as occurring in the deposit.

Elliptio crassidens (Lamarck). A right valve 47 mm. in length is quite characteristic of this heavy-shelled naiad, which is common in the Ohio and Wabash rivers.

Elliptio gibbosus (Barnes). Reported in the deposit by Mr. Fluck.

Actinonaias ellipsiformis (Conrad). A broken right valve and two immature shells (right and left valves) somewhat broken are referred to this common Indiana species. They are thinner, on the average, than recent shells of this species.

Carunculina glans (Lea). A left valve of a female shell 31 mm. in length appears not to differ from recent shells in any important degree.

Lampsilis ventricosa (Barnes). This species is reported from the deposit by Mr. Fluck.

Species incerta cedis.

A portion of the umbonal and lateral tooth region of an unknown naiad also occurs in the material examined. It belongs to the heavy-shelled species, like *rubiginosus* and *undatus*, but is quite unidentifiable.

Sphaeriidae

Sphaerium solidulum (Prime). A number of valves of this common species occur in the material examined, but they are not very characteristic, many individuals varying considerably from the typical form. The young and immature shells are much more typical.

Sphaerium stamineum (Conrad). Three valves of a *Sphaerium* are referred to this species by Dr. Sterki, with doubt.

Sphaerium striatinum (Lamarck). This species is about as abundant in this deposit as *solidulum.* There are many different forms, and the majority of the specimens are young or immature.

Sphaerium fabale Prime. One valve of this characteristic species occurred with the other *Sphaeria*. It is evidently very rare.

Pisidium virginicum (Gmelin). This large *Pisidium* is quite common in this deposit and also quite typical.

Pisidium compressum Prime. This is the most abundant *Pisidium* in the Indiana deposit, as it often is in most recent and fossil collections. The Indiana specimens are more typical than those from the Ohio deposit.

Pisidium cruciatum Sterki. A half-dozen valves, mostly immature, occur in the material.

Pisidium kirklandi Sterki. Fairly common but very characteristic of the species as found living.

Pisidium fallax Sterki. A half-dozen valves, small and slight, are referred to this species by Dr. Sterki.

Pisidium pauperculum Sterki. Two valves of a *Pisidium* are identified with this species by Dr. Sterki.

Pisidium noveboracense Prime. A score of odd valves, small and largely immature, are referred to Prime's species by Dr. Sterki. They are not typical of the species as found living today.

Pisidium abditum Haldeman. Two valves are doubtfully referred to *abditum* by Dr. Sterki.

Valvatidae

Valvata tricarinata (Say). Six young and immature specimens of this carinate *Valvata* were found in the material. The spire is rather depressed and the specimens somewhat resemble *Valvata bicarinata normalis* Walker.

Amnicolidae

Amnicola limosa parva (Lea). A score or more specimens of this variety of *limosa* occurred in the collection. The shells vary from depressed to somewhat elongated. The whorls are all tumid and strongly shouldered at the suture. The spire varies in height and the aperture in rotundity. More than half of the shells are immature.

Amnicola walkeri Pilsbry. A single, large, typical specimen of this *Amnicola* was found in the collection. It is larger than the individuals of the same species from the Ohio deposit.

Amnicola lustrica (Pilsbry). Apparently typical examples of this common *Amnicola* occur more or less abundantly in the Indiana deposit. These are different from the *Amnicola* which occurs so abundantly in the Ohio deposit, and also commonly in the deposits in and about the Chicago region, which has a larger shell with more elongated spire and thickened lip margin. Many of the Indiana shells are immature.

Pyrgulopsis sheldoni (Pilsbry). The presence of this tiny species in these deposits is surprising, the species having been originally described from material collected in Lake Michigan, off Racine, Wisconsin, and dredged from a depth of thirty fathoms (Pilsbry, 1890, Vol. IV, p. 53). Its occurrence in an interglacial deposit far removed from the original locality and in an entirely different ecological environment, a river, is very interesting. These fossils are possibly the ancestors of the species that later restocked the waters of Lake Michigan after the recession of the Wisconsin ice. It should be looked for in other Pleistocene deposits. *Sheldoni* is not uncommon in the Indiana deposit, but the shell is smaller on the average than that of recent specimens. The identification of this tiny species has been confirmed by Dr. Bryant Walker.

Somatogyrus depressus Tryon. The half-dozen specimens of this species are typical.

Pomatiopsis lapidaria (Say). The single specimen occurring in the material is normal in size and general shape, but the whorls are rounder and the sutures more deeply impressed than is usually the case among recent shells of this species.

Pomatiopsis cincinnatiensis (Lea). Four specimens of this smaller species of the genus occurred. They do not differ from recent shells.

Pleuroceridae

Goniobasis semicarinata (Say). A *Goniobasis* abundant in the deposit is referred to Say's *semicarinata* by Mr. Calvin Goodrich, to whom specimens were sent for examination. It is a long-spired, graceful shell which seems very characteristic. In the lot from Bartholomew County there is little variation except in the comparative width of the last whorl.

Viviparidae

Campeloma integrum obesum (Lewis) Tryon. All of the Campelomae in the collection (and these shells are quite abundant) appear referable to this race of *integrum.* A few individuals have a more elongated spire and more ovate shell and might be referred to *integrum.* The variation, however, is all toward the obese type of shell and it seems best to refer all to the race. The majority of the individuals are adult. The shells are quite solid and heavy.

Ancylidae

Ferrissia rivularis (Say). That such fragile shells as the Ancylidae should be preserved in a flood-plain river deposit is surprising. Five specimens of this river limpet occurred in about two quarts of material examined. The specimens are fairly well preserved.

Physidae

Physa crandalli Baker. A heavy-shelled *Physa* with thick, reflexed inner lip and deep-sutured whorls is referred to this species. Only one specimen out of a score or more is adult. The same species has been reported by Daniels from Indiana in the recent fauna of Knox County (Daniels, 1903, p. 603).

Planorbidae

Planorbis antrosus Conrad. The *antrosus* from the Indiana deposit are smaller than those from the Ohio deposit. The aperture does not show a tendency to become bell-shaped as in so many of the Ohio specimens. Only seven individuals, mostly immature, were found in the material from the Indiana deposit.

Planorbis parvus Say. This small *Planorbis* seems to be typical *parvus* and not *altissimus* which is so abundant in the Ohio deposit. It is the same size as specimens of *parvus* from Philadelphia and about half the size of *altissimus.*

Lymnaeidae

Galba humilis modicella (Say). The only lymnaeid in the Indiana deposit is referable to *modicella,* the individuals of which, mostly immature, are similar to the recent shells of this species from the state. *Obrussa decampi,* so common in the Ohio deposit, is apparently not found in these Indiana beds.

Pupillidae

Gastrocopta contracta (Say) = *Bifidaria contracta.* Apparently rare in the deposit as but two specimens were found. These shells are typical but smaller than the average of living *contracta.*

Succineidae

Succinea avara vermeta Say. A single specimen of this race of *avara*, about 5 mm. long, was found in the material. It is, therefore, to be considered as rare.

Endontidae

Helicodiscus parallelus (Say). This common and widely distributed land shell occurred infrequently. The shells are smaller than those of the recent fauna and the spiral striation is but faintly developed.

Pyramidula solitaria (Say). The most abundant mollusk in the deposit. There is considerable variation among the individuals in the height of the spire. The largest specimen measures 30 mm. in greatest diameter. The majority of shells are typically banded. In a few individuals the reddish bands are very wide, leaving a broad peripheral band of white.

Pyramidula solitaria albina (W. G. Binney). A few individuals of *solitaria* without bands occur with the typically banded specimens.

Pyramidula alternata (Say). Found infrequently as compared with *solitaria.* As in the recent shells of this species the fossil examples vary in the height of the spire and in the degree of carination of the periphery of the last whorl. The color varies from albino to the most marked flames of red.

Pyramidula alternata alba (Tryon). Three examples of the albino variety were found associated with the more typical forms. The variety is apparently rare.

Zonitidae

Gastrodonta ligera (Say). This zonitoid land shell occurs rarely in this deposit. The few specimens found are smaller than shells from the recent fauna.

Vitrea indentata (Say). Two immature but characteristic examples of this imperforate *Vitrea* were found in the sand taken from the larger shells.

Vitrea hammonis (Ström.). Two typical specimens of this species were found in the sand from the interior whorls of a specimen of *Pyramidula solitaria*. This small land mollusk, as well as the other species of this family, appears to be very rare.

Circinariidae

Circinaria concava (Say). Not uncommon and as large as the recent shells from Indiana. The aperture is rounder in the fossil shells than in the recent individuals, and the peculiar flattening of the upper part of the outer lip is rarer in the fossil specimens.

Helicidae

Polygyra tridentata (Say). *Polygyra fraudulenta* Pilsbry. These two common species are apparently not abundant in the deposit in question.

Polygyra inflecta (Say). As but two individuals of this species were found in the large quantity of material examined it must be rare among the fossil land shells of this part of Indiana. The shells are apparently normal in both size (12 mm.) and form.

Polygyra profunda alba Walker. Nearly all of the specimens referred to *profunda* belong to the variety *alba*. One individual occurred which has the usual narrow bands on the last whorl and in addition has several large rosy blotches of color on the last half of the body whorl.

Polygyra zaleta (Binney) = *exoleta* (Binney). *Zaleta* is apparently rather rare, only seven specimens being found among several hundred land shells in the material. One specimen has a well-marked parietal tooth; the others are toothless.

Polygyra elevata (Say). Next to *Pyramidula solitaria*, *elevata* is the most abundant land mollusk in the deposit. In size and form they do not differ from the recent individuals. The same variation in height of spire noted among recent shells is also present in the fossil form.

Polygyra thyroides (Say). Of the twelve specimens of this species examined, three have a well-marked tooth on the parietal wall; the others are toothless. There is some variation in size, the extremes being 22 and 28 mm. in greatest diameter.

Polygyra clausa (Say). Characteristic shells of this small *Polygyra* are common in the deposit. These do not differ materially from the recent forms of this species.

Polygyra fraterna (Say). This small *Polygyra* is reported by Mr. Fluck, who has found it more or less common at times.

Polygyra stenotrema (Fer.). Typical forms of this species are not uncommon in the deposit.

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FACTORS PRODUCING COLUMNAR STRUCTURE IN LAVAS AND ITS OCCURRENCE NEAR MELBOURNE, AUSTRALIA

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The following notes on columnar structure owe their origin to a study of the basalt in the Sydenham area, 15 miles northeast of Melbourne, Australia. There, a young stream, Jackson's Creek, has sunk its bed in the Upper Kainozoic lava flows to a depth of 250′. At some points the Silurian and Upper Ordovician sediments are exposed in its bed but at many other places the stream has not yet reached the level of the old valleys and a great thickness of basalt is exposed to view.

The best columns are found along Jackson's Creek in an area $1\frac{1}{4}$ miles in length. In it is a low scoria cone of the same age as the lava. Three miles to the north is a line of volcanoes from which the later lava floods came. Of the columns the best perhaps are those known as the Sydenham Organ Pipes. These are 102′ high, are perfectly developed, and give examples of the various structures discussed in this short paper.[1]

1. *Cause of columnar structure.*—The attitude, size, shape, and regularity of the columns depend upon (*a*) the viscosity of the lava; (*b*) the temperature of the lava; (*c*) the rate of cooling; (*d*) the regularity of cooling; (*e*) the homogeneity of the lava. Shallow surface flows are much disturbed by movement and are usually distorted by folded-in masses of scoriaceous material, so that homogeneity is lost. Cooling is irregular and columns do not form. The importance of homogeneity as a factor in columnar formation cannot be emphasized too much. The great controlling factor in the formation of columns is contraction due to cooling. The rock, on cooling, tends to contract but all solids have the power to extend somewhat under tension. When the tension due

to contraction on cooling is able to overcome this power of extension, the rock cracks.

Let us consider in the first place a lava mass cooling from one surface only, the top of the flow (Fig. 1). It is evident that the surface will cool very rapidly owing to the scoriaceous nature of the surface, the convection currents in the air above the heated rock, the volcanic rain (if near a vent), and the collection of water on the warped surface. Thus a solid crust will form over the molten lava and this liquid will cool very slowly because rock is a very poor conductor of heat. While cooling and shrinking in the liquid state, it will adjust itself to the tension by a movement of the liquid, but when the lava solidifies from *b* to *c* (Fig. 1) the rock is subjected to tension in horizontal and vertical directions. The vertical tension is relieved by movement of the liquid beneath *c* and by the shortening of the column *bc*. Vertical tension at this stage does not cause joints in the rock but the horizontal tension can only be relieved by cracking. Mallet[1] puts the temperature of cracking between 315° C. and 500° C., and points out that the temperature is lower when the rate of cooling is very slow. He also shows that if the rock were perfectly homogeneous the surface would be covered with cracks separating the surface into equal areas, i.e., triangles, squares, or hexagons.[2] The smallest amount of work is done by separating the surface into hexagons rather than into squares or triangles. These cracks would extend down into the hot solid rock only a short distance, i.e., to that point where the tension was equal to the extensibility. As the rock cooled, the cracks would extend downward and at the same time the deeper liquid lava would be solidifying and shrinking from two causes: cooling and crystallization. The slower the cooling the more complete the crystallization and therefore the greater the contraction. We

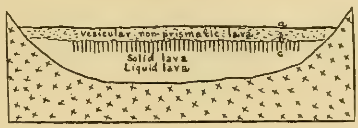

FIG. 1.—Section showing how columns are formed in the brittle solid lava, when tension due to contraction overcomes the expansive power of the lava. Columns are not formed near the surface.

[1] R. Mallet, *Phil. Mag.*, L (1875), p. 130.

[2] *Op. cit.*, pp. 125–30.

thus see that in a homogeneous lava, vertical cracks arranged in hexagons, slowly penetrate the solid lava from above, downward. Solidification of the lava precedes the cracking.

The size of the columns depends chiefly on the temperature and rate of cooling. The more rapidly cooled a flow is the thinner will be the columns.

Owing to the fact that lava masses are seldom homogeneous (on account of included gases, convection currents within, variation in chemical composition, included fragments, etc.) it seldom, if ever, occurs, that only hexagonal prisms are formed. It does not need the fact that olivine crystals have been found divided by vertical joints, nor the preservation of flow structure in glass to show us that the splitting took place in solid lava.[1] It is difficult to imagine liquid or even plastic lava cracking. Tension in that case is relieved by flowage, not by cracking.

For the following reasons the writer believes that columnar structure in basalt is due to slow rather than rapid cooling:

1. Basalt has a very low thermal conductivity and therefore great thicknesses of molten basalt must necessarily cool slowly. The fact that columnar basalt is not well developed where flows are thin appears to be due to two factors: (*a*) heterogeneity of the lava, (*b*) rapid cooling of the thin flow.

2. Cracking takes place in the hot solid rock when the contraction becomes greater than the expansion under tension. The rock is able to resist parting for a longer period when the tension is very slowly increased by slow cooling. If tension is more rapidly increased the flow will break into thin columns or fragments. These statements are based on physical laws. The rate of cooling at the upper surface is much more rapid than at the lower because convection currents in the air above rapidly convey away the heat but the valley floor being a poor heat conductor offers much resistance to the transference of heat. In a thick flow, columns grow from all cooling planes. The upper columns are found to rest on thick basal columns and this fact upholds the statement that the size of columns is determined by rate of cooling.

[1] J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886), p. 324; R. B. Sosman, *Jour. Geol.*, XXIV (1916), p. 218.

3. The fact has frequently been recorded[1] that the upper layer of rock is not columnar but fragmental, platy, ropy, or scoriaceo This fact shows that if cooling is rapid, columns are not formed, for the surface layer is cooled with very great rapidity. If cooling is very rapid contraction is likely to cause fragmental partings since the isothermal planes would probably be irregularly spaced through the flow.

4. In the rock sections of columnar basalt examined very little glass was noted, whereas the surface rock contained a considerable amount of glass. The holocrystalline nature of the columnar basalt strongly suggests slow rather than rapid cooling.[2]

2. *Ball-and-socket structure.*—The cross joints are secondary, i.e., they are formed after the columns. This is shown by the fact that they never continue across from one column to another. The vertical columns continue to shrink as they cool. Horizontal contraction simply causes a widening of the vertical joints, but tension in other directions can only be relieved by cracking.

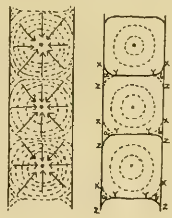

FIG. 2 FIG. 3

FIGS. 2 and 3.—Onion structure and spheroidal weathering. Centers of contraction along the columns cause concentric planes of weakness which, on weathering, develop into the well-known "onion structure." The solid angles *a* and *b*, which tend to break off, are due to these concentric planes of contraction. Ball-and-socket joints are formed between the adjacent spheroids.

There are necessarily centers of contraction distributed equally along each column (if lava is homogeneous) and the particles will concentrically be drawn toward these points. This causes not only concentric weakenings and cracking but also a well-defined horizontal joint midway between any two centers of contraction (Fig. 2). Mallet[3] says that the concave surfaces face the direction of cooling. This is not true in the areas I have studied, for adjacent columns have the cups facing directions regardless of the cooling surface.

[1] J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886), p. 325. [2] *Op. cit.*, p. 331.

[3] R. Mallet, *Phil. Mag.*, L (1875), p. 204; J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886), p. 329; R. B. Sosman, *Jour. Geol.*, XXIV (1916), p. 229.

We can say that either the convex or the concave surface faces the direction of cooling. It is also evident that the solid angles, *a* and *b*, are likely to be broken off along *YZ* and *YX* (Fig. 3), since these are planes of contraction and weakness. This seems to explain very simply a well-recognized structure that has given rise to much debate[1] (Fig. 3).

Fig. 4.—"Dutch-cheese" structure. Each spheroid is about eight inches thick. ("Organ Pipes," Sydenham, Australia.)

The above explanation for the ball-and-socket structure also explains the prevalence of spheroids in the columns. I cannot believe that they are due to weathering[2] or segregation, but rather to the concentric spheres of contraction. The spheroids are not found passing from one column to another. In the diagram (Fig. 3) each column is seen to be divided actually or potentially into blocks, each composed of concentric spheres separated by a contraction crack or line of weakness along which weathering will later take place and finally give rise to "onion structure."

3. "*Dutch cheeses.*"—This structure is very common on slightly weathered basalt columns (Fig. 4). The oblate spheroids are seen piled one above the other. They appear to be oblate for this reason: Contraction along *ax* (Fig. 5) is easier than along *ab*,

[1] T. G. Bonney, *Quart. Jour. Geol. Soc.* (1876), p. 153; R. Mallet, *Phil. Mag.*, L (1875), p. 205; J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886); R. B. Sosman, *Jour. Geol.*, XXIV (1916).

[2] J. Thomson, *British Association Reports* (1863), p. 89; R. Mallet, *Phil. Mag.*, L (1875), p. 220.

because no tearing apart of the crystals is necessary along *ax*. In order that tension in all directions may be approximately equal, *am* must be shorter than *ax*. Therefore, the shape of the spheroids is dependent on the ratio of the tension between *ax* and *am*. The shape of the spheroids is also dependent on the downward pressure of the columns. This pressure tends to resist horizontal cracking and therefore the greater the downward pressure the more prolate the spheroid will be. The actual shape of the spheroid is determined by the downward pressure of the column tending to make it prolate, and the difference in tensions along *am* and *ax* which tends to make the spheroid oblate.

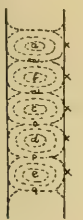

FIG. 5.—Dutch-cheese structure. The shape of the spheroids depends on the balance between the difference in tension between *ak* and *am*, which tends to make the spheroid oblate and the downward pressure of the column tending to make the spheroid prolate.

4. *Chisel structure.*—At the "Sydenham Organ Pipes" horizontal markings $\frac{3}{4}''$ to $2''$ apart, are seen

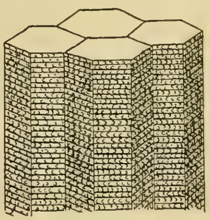

FIG. 6

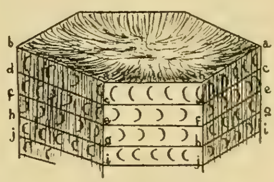

FIG. 7

FIGS. 6 and 7.—Diagrammatic section showing horizontal bandings *abab*, *cdcd* round the columns. Rough chiselings are shown on each band.

circumscribing most of the columns (Figs. 6, 7, and 9). The horizontal lines are found along the whole length of the columns and between them there are peculiar irregularly curved lines similar to those made by roughly chiseling wood (Figs. 7 and 9). The horizontal lines appear to represent successive stages in which the columns were formed, i.e., as cooling proceeded, the vertical plane *abcd* extended to *ef*, then to *gh*, and so on. The "chiselings" curve sometimes to the left, sometimes to the right, and are probably due to the heterogeneity of the rock as it parted.

5. *Columns formed by cooling from two opposing surfaces.*—Cooling takes place not only from the upper surface but also from

the floor. The upper surface rapidly parts with its heat by air convection currents and convection along the vertical joints. Heat is only slowly lost from the bottom surface because convection in

FIG. 8.—"The Organ Pipes." These basaltic columns are 102′ high and are found on Jackson's Creek, Sydenham, Australia.

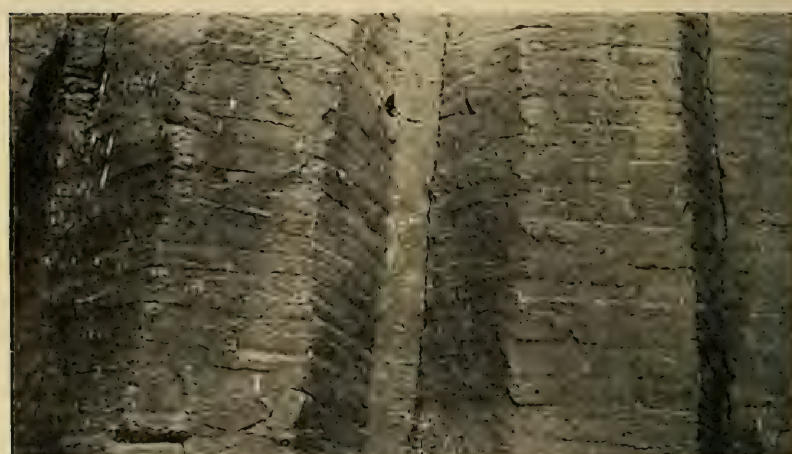

FIG. 9.—Chisel structure. Several basaltic columns are shown with characteristic horizontal banding. In each band the chisel structure can be seen. ("Organ Pipes," Sydenham, Australia.)

the liquid rock seems to be comparatively unimportant, the conductivity of the rock beneath is very low, and the loss of heat by rising gases is unimportant in lowering the temperature of the bottom layers. The isothermal planes will therefore be widely separated in the upper layers and closely packed together in the lower. Two sets of columns will be formed. The upper are long, thin, and often irregular, while the lower set are short, thick,

Fig. 10.—Weathered chisel structure. The chisel markings have been weathered off but the horizontal bandings have developed into platy structure. (Jackson's Creek, Digger's Rest, Australia.)

and much more perfect, owing to the homogeneity of the lower lava (Figs. 11 and 12).

It must be remembered that straight hexagonal columns are produced only in regularly cooling, quiet, homogeneous lavas. The upper part of the flow is more heterogeneous than the lower because (*a*) gases from the lower layers are irregularly distributed near the top; (*b*) the upper surface is churned to some extent by the movement; (*c*) volcanic rain percolates the vesicular lava; (*d*) water may collect on the partially cooled lava. These four factors tend to produce a heterogeneity in the upper part of the flow and therefore only very imperfect columns, if any, are formed.

As the thin upper and the massive lower series of columns approach one another their direction will be influenced by the plane of the isotherms of each series. Both sets are perpendicular to the planes of the isotherms (Fig. 13). Finally the two planes merge into one another and if both sets of columns are vertical, there will be a straight horizontal plane junction which simulates the junction between two lava flow (Figs. 11 and 13), but the absence

FIG. 11.—Junction of the upper and lower columns of a lava flow. The sharp division suggests the junction of two flows, but only one flow is represented. The lower columns are much more massive than the upper. (Jackson's Creek, Sydenham, Australia.)

of vesicles and scoriaceous material, the exact similarity in density and texture of the two series at their junction, and the actual blending of the columns at times show that they belong to the same flow.

The resting of thinner columns on more massive basal ones is very common. They are described by Scrope[1] and Iddings[2] and are well shown at Sydenham. Dykes commonly show the edge of the division plane between two sets of columns.

[1] G. P. Scrope, *Volcanoes* (1862), p. 94.

[2] J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886), p. 322.

6. *Columns formed from inclined cooling surfaces.*—The dotted lines on Figure 13 represent the edges of the isothermal surfaces. Columns form at right angles to these surfaces. The isotherms shown in Figures 12 and 13 give data for the rate of formation of the columns, their size, and their direction. The closer the isotherms the larger are the columns because the lava is able to resist a greater tension without cracking when that force is gradually applied. Columns from the two inclined surfaces approach one another and meet along a major joint plane which would be enlarged by drainage. Note that along this major joint the columns curve toward the higher temperatures.

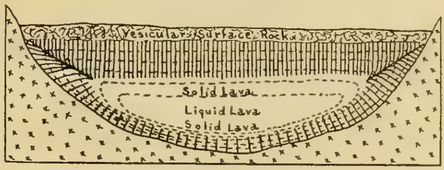

FIG. 12.—Section showing lava cooling from two surfaces, and columns penetrating the solid lava as cooling proceeds. Columns are perpendicular to the isothermal planes and where two cooling surfaces are inclined to one another a major joint plane separates the two sets of columns.

7. *Bent columns.*—These (Fig. 14) are formed in cases where the isotherms are not parallel to one another. For reasons such as those enumerated below, the cooling in one direction is more rapid than in another. The columns bend in the direction of greatest cooling (Fig. 15). Dotted lines represent edges of isothermal surfaces. The following are suggested causes for change in direction of cooling: (1) presence of scoria, etc., in close proximity to the lava; (2) irregularities in the valley floor; (3) the warping of the lava's upper surface; (4) a scoriaceous and vesicular surface; (5) included gas, water, etc., in the lava; (6) convection currents in the air above the lava; (7) convection currents in the lava; (8) penetration of water into the lava and scoria; (9) rain from the volcano; (10) movement

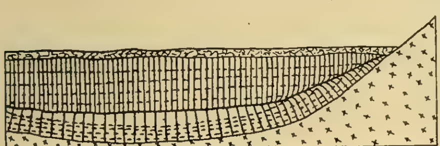

FIG. 13.—Junction of the slender upper columns and the massive basal columns of a lava flow. The junction somewhat resembles the junction between two lava flows.

of the liquid or plastic lava and thereby of the isotherms; (11) rise of steam from an overwhelmed stream; (12) chemical variation in the lava with corresponding change in thermal conductivity.

Fig. 14.—Bent columns. (Jackson's Creek, Sydenham, Australia.)

It is not likely that lava columns bend after they are formed, for if lateral pressure were sufficiently strong, it would fracture the brittle columns but not bend them. The plastic state, when the lava would yield to lateral pressure, was lost when the molten mass crystallized.

8. *Convection as a factor on column production.*—R. B. Sosman[1] in 1916, stated that many, if not most, lava columns were due to convection currents in the molten flow. He said convection columns are characterized by the fact that hexagonal columns and angles of 120° predominate, while the majority of contraction columns are pentagonal.[2] After testing some hundreds of columns in the Sydenham area I am unable to agree with him in several respects. The attitude of the columns there stamps them as being definitely due to contraction, not convection, and yet 40 per cent are hexagonal, 22 per cent heptagonal, 22 per cent pentagonal, 13 per cent octagonal and 3 per cent quadrilateral, and the great majority of the angles are

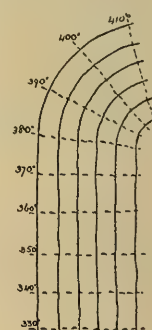

Fig. 15.—Bent columns. Diagram showing the relation of the attitude of the columns to the isothermal planes.

[1] R. B. Sosman, *Jour. Geol.*, XXIV (1916), pp. 224, 228, 233.

[2] *Ibid.*, pp. 225–26.

between 120° and 130°. From these observations it is clear that it is not safe to classify columns as due to contraction or convection by their shape and angles.

Close to the "Sydenham Organ Pipes" there are a number of huge squat irregular basaltic columns about 10′ in diameter. The flow is thin and the shape of the great blocks seems to be determined by convection which left its record in them by vesicles and when the rock contracted through loss of heat the cracks formed along the lines of vesicles (Fig. 16). The vesicles are pulled round in just the way one would expect if convection currents were the cause. There are centers round which the currents traveled and these tend to be hollowed out leaving holes 3′ to 4′ across. It is possible that the drawn-out vesicles are due to the movement of the lava before it came to rest, but the fact that most of these squat columns seem to have the hollow or nucleus suggests convection. Contraction due to shrinkage subsequently tends to crack the rock along the lines where the currents rose or sank.

FIG. 16.—Convection currents in basalt. The direction of the vesicles and the occurrence of the nuclei suggest that the molten lava was disturbed by convection currents. The vertical joints occur where the long axes of the vesicles are vertical.

Convection columns in this area are either very unimportant or absent so that the conclusions drawn in R. B. Sosman's paper in the *Journal of Geology*, 1916, do not find confirmation in the area above described.

Reviews

Kaolin of Indiana. By W. N. Logan, State Geologist. Indiana State Dept. of Conservation, Bull. No. 6, 1920. Pp. 131, pls. 43, maps (colored) 7.

Beds of kaolin occur at several horizons at or near the top of the Mississippian formation in several counties in southwestern Indiana. One important horizon is at the contact between a Chester shale (below) and a Pottsville sandstone (above). All the beds are beneath a sandstone and above a shale. There has been only a slight commercial development of the deposits to date, in spite of the presence of large quantities of high-grade white clays. The report discusses (1) the physical and chemical properties of Indiana kaolin; (2) its geological conditions of occurrence; (3) its origin; and (4) its uses. It also gives (5) its geographic distribution by counties.

Dr. Logan's study of the origin of Indiana kaolin has disproved earlier explanations. Laboratory experiments and microscopic examination have shown that this kaolin is due to biochemical action, an origin not before suspected. It was found that under proper conditions in the laboratory, sulphur bacteria secrete kaolin. In nature, sulphur bacteria obtain sulphur from the iron pyrite in the shale. The sulphuric acid which is formed, attacks the aluminum in the shale. The resulting compound reacts with the quartz of the sandstone, and the sulphur is replaced by silica, producing kaolin.

As kaolin in southern Indiana is being actively formed today by sulphur bacteria where the average annual temperature is 50° F., it is inferred that the kaolin deposits of the Tuscaloosa, Wilcox, and Lafayette formation of southern states were formed under similar temperatures. During the glacial epochs, some such average temperature doubtless occurred in the Gulf states.

S. S. V.

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VOLUME XXVIII NUMBER 6

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SEPTEMBER-OCTOBER 1920

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Diastrophism and the Formative Processes. XIII. The Planetesimals and Their Infall. By T. C. Chamberlin.

Geologic Reconnaissance of the Southern Part of the Taos Range, New Mexico. By John W. Gruner.

Summaries of Pre-Cambrian Literature of North America. Papers II–VII. By Edward Steidtmann.

A Test of the Feldspar Method for the Determination of the Origin of Metamorphic Rocks. By C. G. Carlson.

A Pleistocene Peneplain in the Coastal Plain. By H. F. Cleland.

On Some Physical Properties of Ice. By Motonori Matsuyama

The Mineralography of the Feldspars. By H. L. Alling. To be published as a supplement to the *Journal of Geology*.

VOLUME XXVIII NUMBER 6

THE

JOURNAL OF GEOLOGY

SEPTEMBER-OCTOBER 1920

DIASTROPHISM AND THE FORMATIVE PROCESSES

XII. THE PHYSICAL PHASES OF THE PLANETARY NUCLEI DURING THEIR FORMATIVE STAGES

T. C. CHAMBERLIN
The University of Chicago

In an article in the first number of this volume of the *Journal* a study of the relative densities of the moon, Mars, Venus, and the earth brought out the fact that the mean densities of these bodies not only rise in the order of their masses, but that the rate of increase itself rises with each unit-increase of mass.[1] This led to a study of the processes by which these bodies acquired their material, to see whether any part of the observed higher density could reasonably be assigned to greater proportions of inherently heavy material received during their formation. The conclusion was reached that larger proportions of *light* material entered into the formation of the large bodies than into the small bodies. The natural inference from this is that the higher mean densities now found in the larger bodies are due to some form of mass-effect that was sufficient to

[1] "The Order of Magnitude of the Shrinkage of the Earth deduced from Mars, Venus, and the Moon," *Jour. Geol.*, Vol. XXVIII (1920), pp. 1–17. Compare this with the theoretical deductions of Dr. A. C. Lunn, "Geophysical Theory under the Planetesimal Hypothesis, in the Tidal and Other Problems," *Carnegie Institution Publication No. 107* (1909), particularly pp. 188 and 201. Compare also the very suggestive paper of Dr. Wm. D. MacMillan "On Stellar Evolution," *Astrophys. Jour.*, Vol. XLVIII (July, 1918), pp. 36–40.

overbalance their higher content of light original material.[1] It was recognized, however, that the inquiry could not be regarded as having covered all the shrinkage phases of this mass-effect until the physical states of the four bodies during their formation were considered. Under the planetesimal hypothesis their formation embraced two phases: (1) the progressive concentration of those portions of the solar outbursts that were held together by their mutual attractions so as to act as unit assemblages and thus serve as collecting centers or nuclei; (2) the gathering into these nuclei of such scattered parts of the solar outbursts as were dispersed into planetesimal orbits from which they could be picked up only individually. The first process started with a gaseous body and followed the gaseous line of descent; the second was concerned with individual bodies and orbital dynamics. This paper is confined to the first of these.

THE SUCCESSIVE PHYSICAL PHASES ASSUMED BY THE NUCLEI IN PASSING FROM THEIR ORIGINAL CONDITION TO THEIR FINAL STATES AS PLANETARY CORES

There is a wide range between the largest planet and the smallest planetoid. There may also be wide differences of view respecting the probable sizes of the nuclei. As I wish to leave the question of the nuclear masses freely open for the present, it seems best to treat broadly the whole group of solar dependents, including planets, planetoids, and satellites. There is the additional reason that their gradations, their likenesses, and differences, as well as the contrasts of their extreme developments, form the natural background for the special cases with which we are particularly concerned in this discussion.

It is assumed that each one of the present planets, planetoids, and satellites started from a nucleus inherited from a solar outburst. It is held that some of these nuclei were formed from the central portions of the solar outbursts, while others were merely segments detached from these. Some of the detached segments are supposed to have remained under the control of the central portions and become satellites, while others pursued orbits of their

[1] "Selective Segregation of the Earth and Its Neighbors," *Jour. Geol.*, Vol. XXVIII (1920), pp. 126–57.

own and became planetoids. These are regarded as natural results of solar eruptions under exceptional stimulus from a passing body.[1]

As the assigned result of this there arose a very significant series of solar attendants of cognate birth and linked together by gradations, though the extremes were quite highly differentiated. The series, as now presented, ranges from massive hot gaseous planets of low densities, down through intermediary forms, to quite small solid bodies of high densities and altogether devoid of appreciable atmospheres. In mass value the largest planet is several million times the smallest planetoid—probably we could say several billion times, if the lower limit of the planetoids were accurately determined. In Table I this great series is listed in the order of size, neglecting the common distinction between planets, planetoids, and satellites, which is immaterial in this particular study. The physical differences are brought out by groupings. It will be seen that the planets, planetoids, and satellites are notably mixed in the lower part of the list. The gradation would doubtless be much closer and the classes even more intermixed, if the sizes of all the smaller bodies were well enough determined to permit a strictly accurate arrangement of the smaller masses. There are now known to be 26 satellites and upward of 800 planetoids, most of which seem to be less than 100 miles in diameter.

While in general there is a notable gradation, there is yet a wide gap between the giant group of gaseous planets and the terrestrial group next below, which are essentially solid but have gaseous envelopes. Within the latter group a somewhat notable difference in mass sets off the earth and Venus from Mars. The scant atmosphere of the last allies it to the atmosphereless group below and its nucleus not unlikely belonged to that class.

The differences in the groups suggest that the formative processes, though of the same type and initiated in the same way, entered in such different proportions into the actual formative work that they gave rise to very divergent results. This tallies with our earlier suggestions that the formative agencies embraced within

[1] See the special cases of May 29 and July 15, 1919, outlined in this *Journal*, Vol. XXXVIII (February–March, 1920), pp. 145–49, or the original description by Pettit, in *Astrophys. Jour.*, Vol. L (October, 1919), pp. 206–19.

themselves opposing factors (VII of previous article)[1] so poised as to permit a ready shifting of dominance from one side of the

TABLE I

THE SOLAR DEPENDENTS GRADED BY SIZE AND GROUPED BY PHYSICAL PROPERTIES

A. THE GIANT GROUP. HIGHLY GASEOUS BODIES

(Densities low; diameters between 30,000 and 90,000 miles)

	Densities	Diameters in Miles
Jupiter	1.25	88,392
Saturn	0.63	74,163
Neptune	1.09	34,823
Uranus	1.44	30,193

B. THE MEDIAL OR TERRESTRIAL GROUP. SOLID BODIES BEARING ATMOSPHERES

(Densities high; diameters between 4,000 and 8,000 miles)

	Densities	Diameters in Miles
Earth	5.53	7,918
Venus	4.85	7,701
Mars	3.58	4,339

C. THE DIMINUTIVE GROUP. ATMOSPHERELESS SOLID BODIES

(Densities high; diameters ranging from 3,600 miles down to the lower limit of estimating power)

	Bodies	Diameters in Miles
Satellite	Jupiter's III	3,558
Satellite	Jupiter's IV	3,345
Planet	Mercury	3,009
Satellite	Saturn's VI	3,000

THE DIMINUTIVE GROUP—*Continued*

	Bodies	Diameters in Miles
Satellite	Jupiter's I	2,452
Satellite	The Moon	2,100
Satellite	Jupiter's II	2,095
Satellite	Saturn's VIII	2,000
Satellite	Neptune's VIII	2,000
Satellite	Saturn's V	1,500
Satellite	Saturn's III	1,200
Satellite	Saturn's IV	1,100
Satellite	Uranus's I–IV	500 to 1,000
Satellite	Saturn's II	800
Satellite	Saturn's I	600
Satellite	Saturn's VII	500
Planetoid	Ceres	485
Planetoid	Pallas	304
Planetoid	Vesta	243
Satellite	Saturn's IX	200
Planetoid	Juno	118
Planetoid	Several exceeding	100
Satellite	Jupiter's I	100
Planetoids	Probably 700 or more, ranging downward from	100
Satellite	Mars's II	...
Satellite	Mars's I	10
Satellite	Jupiter's VI and VII	"small"
Satellite	Jupiter's VIII and IX	"very small"

Planetoids. The smallest order of planetoids probably form the lower end of the series, ranging down to 10 or perhaps even 5 miles.

balance to the other, thus giving rise to a series of widely varying effects which at the extremes even became contrasted. The preponderance in the upper end of the series lay markedly on the

[1] "Selective Segregation of Material in the Formation of the Earth and Its Neighbors," *Jour. Geol.*, Vol. XXVIII (1920), pp. 126–57.

side of gas accumulation, while in the lower part the dominant effect lay in the dissipation of all gas. In the middle ranges there was a closer approach to equipoise between these extremes and hence to a mixed product of the medial order. It is thus clear that the genetic processes, however alike basally, were capable of giving such different results as to make it necessary to study with care and patience the balancings between opposing influences and the differential effects of the shifting of these balances.

THE CRITICAL CONDITIONS THAT CONTROLLED THE PASSAGE OF THE NUCLEI INTO COLLECTING CORES

The original diversity of the nuclei is assigned to differences in the impulses imparted by the solar eruptions. The evolution of the nuclei, after being launched on their several careers, was critically dependent on the dynamic properties which they inherited individually. These now require attention. We need not dwell, however, on the giant gaseous planets, for they do not fall within the range of our present problem, nor do they seem to have ever passed through the more critical phases of the processes we are about to consider. They probably had, at the outset, nuclei massive enough to hold essentially all their own gases in spite of their molecular activity and to retain essentially all alien molecules that plunged into them.[1]

To cover the whole field of the known solid bodies in a representative way, Table II is introduced. It gives certain essential dynamic properties for ten typical bodies, four natural and six ideal, so selected as to represent at convenient intervals the whole range from the earth—the largest known solid body—down to a ten-mile planetoid. Dr. W. D. MacMillan has been kind enough to make the computations for this table.

It seems improbable that the nuclei of the earth, Venus, Mars, or the moon, even at their smallest stages, were so diminutive as the lower orders of ideal bodies in Table II, but these very small bodies are even more serviceable than larger ones in illustrating the critical conditions that attended their formation and measurably that of

[1] The inevitable loss of such molecules as attained very exceptional speeds is neglected throughout this discussion.

the larger bodies of the solid order. They thus serve to put to severe test our notions as to the formation of such bodies. It will not be surprising if we find that these small bodies lie on the precarious border that separates successful aggregation from dissipation into planetesimals.

TABLE II

DYNAMICAL PROPERTIES OF TEN REPRESENTATIVE BODIES OF THE TERRESTRIAL AND SMALLER CLASSES

THE TEN BODIES		STATISTICAL PROPERTIES			DYNAMICAL PROPERTIES			
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*
No.	Name	Diam. in Miles	Density Water=1	Mass Earth=1	Surface Gravity g=1	Parabolic Velocity in Miles per Sec.	Velocity of Retention in Miles per Sec.	Diameter of Sphere of Control
I.	Earth	7918	5.53	1.0000	1.00	6.95	4.91	1,240,000
II.	Venus	7701	4.85?	0.807?	0.85	6.33	4.48	1,156,000 (836,000)
III. . . .	Mars	4339	3.58	0.1065	0.36	3.06	2.16	588,000 (898,000)
IV.	Ideal	3407	3.50	0.050	0.27	2.38	1.68	458,000
V	Moon	2160	3.34	0.0122	0.16	1.47	1.04	286,000 (50,000)
VI.	Ideal	1000	3.30	0.001202	0.075	0.68	0.48	132,000
VII . . .	Ideal	500	(*a*) 3.30 (*b*) 5.00	0.0001503 0.000228	0.0375 0.057	0.34 0.42	0.24 0.30	66,000 76,000
VIII. . .	Ideal	100	(*a*) 3.30 (*b*) 6.00	0.000001202 0.000002186	0.0075 0.0137	0.068 0.123	0.048 0.087	13,200 16,000
IX. . . .	Ideal	50	(*a*) 3.30 (*b*) 6.50	0.0000001503 0.0000002960	0.00375 0.0074	0.034 0.067	0.024 0.047	6,600 8,200
X.	Ideal	10	(*a*) 3.30 (*b*) 7.00	1.202×10^{-9} 2.550×10^{-9}	0.00075 0.00160	0.0068 0.0144	0.0048 0.0102	1,320 1,700

The selections are adapted to the earth as unit and the spheres of control are based on the earth's distance from the sun. An ideal body $\frac{1}{20}$ the mass of the earth is introduced between Mars and the moon to better grade the series, and for a like reason an ideal body 1,000 miles in diameter is introduced below the moon. The four ideal bodies, 500, 100, 50, and 10 miles in diameter, respectively, are selected to cover the range of the planetoids and smaller satellites. The largest of planetoids thus far measured satisfactorily is 485 miles in diameter (Barnard). Two hypothetical densities are assigned to each of these, the one to represent bodies supposed to be composed largely of stony matter, the other to represent those that may have a notable content

of iron. In the 10-mile body this higher density is put at 7, which is thought to be as dense as any such natural aggregate, inevitably more or less mixed and porous, would be likely to be.

Column *f* gives the maximum acceleration of gravity at the surface of the given body, stated in percentages of the acceleration of gravity at the surface of the earth. Column *g* gives, in miles per second, the parabolic velocity (= velocity required to give to a projected body a parabolic path = velocity capable of carrying a body to infinity = velocity acquired in a free fall from infinity = "velocity from infinity"). In discussions of the limitations of atmospheres, this "velocity from infinity" has very commonly been used erroneously as "the critical velocity of escape," but by referring to column *i* it will be seen that a molecule shot away from these bodies may reach the limit of the body's control very much short of an infinite distance. If one wishes to show that the molecules *must escape*, and desires to make his statement conservative by leaving a good "margin of safety" to cover defects in data and otherwise, the parabolic velocity is a very suitable criterion to use. If, on the other hand, one wishes to show that molecules *will be retained*, and desires, as before, to leave a margin of safety for retention somewhat above that, the figures in column *h* form convenient criteria. Strictly speaking, these represent the velocity required to give a particle a circular orbit at the surface of the body, and this velocity forms a dividing line between the ordinary collisional atmosphere and the orbital ultra-atmosphere. The latter forms the transition stage through which molecules may escape from control with the least velocity. The velocity in a circular orbit has a fixed ratio to the parabolic velocity for the same point, viz., $1:\sqrt{2}$. The figures for the parabolic velocity and for the velocity of circular orbit or "velocity of retention" each becomes lower as the points of reckoning rise above the surface. The minimum velocities required for escape lie between the velocity for circular orbit and the velocity of fall from the limit of the sphere of control and are dependent on the mode of escape.

Column *i* gives the diameters of the spheres of control of the several bodies in competition with the sun *at the earth's distance*. It is important to note the qualifying clause, for spheres of control vary with the distance from the controlling body. The *actual* spheres of control of Venus and Mars are given in parenthesis. For the present discussion spheres of control at the distance of the earth are most serviceable. In the case of the moon, the figure in parenthesis represents the moon's sphere of control *as against the earth*, within whose sphere of control it revolves.

It is worthy of note that the spheres of control at the lower end of the series, notwithstanding their diminution, still have notable dimensions. These spheres of control give concrete pictures of the areas over which the several bodies exercise collecting as well as holding power, while the figures in columns *g* and *h* give data for realizing, in terms of velocity, how limited is the power of this influence in the smaller masses.

The table would be additionally helpful if the central pressures, the central densities, and the central temperatures could each be given in terms equally trustworthy, but determinations of these properties rest on a much less secure basis. The central pressures can only be determined by assuming some law of downward increase of internal density. The actual rate of such increase is uncertain, beyond the fact that it must fall within certain rather broad limits defined by precession and other astronomical phenomena whose requirements are not precisely determinable. Laplace's theoretical law of density is perhaps the most plausible and is the one commonly used in preference to such others as have been proposed. Using it, MacMillan finds the central pressure of the 10-mile body, when assigned a mean density 3.30, to be only 11.8 lbs. per square inch, i.e., less than the pressure of the earth's atmosphere. On the other hand, that of the present earth is 22,500 *tons* per square inch, or about 3,000,000 atmospheres. The results given by Laplace's law are in general accord with those obtained earlier in this discussion from a comparison of the moon, Mars, Venus, and the earth.[1] However, reserve in placing implicit confidence in this law is to be observed, for by carrying the series of determinations upward from the earth on the same basis, MacMillan finds that at a radius of about 5,000 miles the central density becomes infinite. This seems to mean either that the law breaks down or else is rendered inapplicable by some intercurrent factor whose nature is as yet unknown. Dr. A. C. Lunn reached results of similar import in his geophysical studies under the planetesimal hypothesis in 1909.[2] The suggestive correlation of the densities of the whole series of planets made by MacMillan in his paper "On Stellar Evolution" deserves thoughtful consideration in this connection.[3]

It is clear, then, that until some elucidation is found for this singular result so shortly reached after the dimensions of the earth are passed, it is unsafe to build important conclusions upon the law.

[1] "The Order of Magnitude of the Shrinkage of the Earth Deduced from Mars, Venus, and the Moon," *Jour. Geol.*, Vol. XXVIII (1920), pp. 1–17.

[2] "The Tidal and Other Problems," *Carnegie Publication No. 107* (1909), pp. 201–2.

[3] *Astrophys. Jour.*, Vol. XLVIII (July, 1918), pp. 36–40.

In reaching conclusions respecting the central temperature there is not only the danger of error due to deducing it from compression computed according to this doubtful law, but there are other sources of uncertainty, among which one of the more serious is the unknown amount of heat removed by inherited eversive movements within the body, co-operating with ordinary convection while the formative processes were in progress, and since. In the distinctly large bodies these might not perhaps rise to decisive value, but in the smaller orders of bodies the central temperature theoretically assignable to concentration might be so far dissipated by the combined effects of inherited eversive movements, convection, conduction, and viselike mechanical action (discussed below) that it would have but limited effect on the physical state of the core into which the nucleus passed.

A further serious difficulty in estimating central temperature arises from our ignorance of what part of the potential energy theoretically set free by compression went into endothermal reorganizations, what part became latent in forming solutions, what part was carried surfaceward by the forced ascent of these solutions, and what remained to increase the temperature.

THE GROUP OF FACTORS THAT CONDITIONED THE PROCESS OF NUCLEAR CONCENTRATION

The passage of the planetary nuclei from their original states as solar gases into their final states as the cores of planets, planetoids, and satellites was by no means so simple a process as gaseous condensation has usually been regarded. Beside the simple condensing process, as usually considered, there were co-operating activities that radically modified the general tenor of the process. Four of these require consideration:

I. *Several types of motion were inherited from the solar eruption, and these took the lead in determining the internal circulation. The thermal convection, as it arose, was superposed on these.*

II. *A sifting of the mixed molecules of the original gaseous matter set in almost as soon as it emerged from the sun and changed the mixture to the proper proportions for forming planetary cores.*

III. *The formation of precipitates also set in early, and gradually changed the primitive gases into Brownian mixtures which themselves*

changed as time went on. In the smallest order of bodies this precipitation, together with the escape of such molecules as remained free, went so far ultimately that the residues were reduced to clouds of precipitates which condensed in a way of their own.

IV. *Almost as soon as cores began to form, differential stresses, more intense below than above, were brought to bear upon them by external agencies which aided in working the lighter and more mobile materials toward the surface, thus developing increasing density and solidity in the central parts.*

In discussing these co-operating factors it will be helpful to have in mind concrete pictures of the deployment of the matter under study, fashioned in the form of spheres of control, for these best bring out the dynamics of the organizing work. The matter in spheres of control may be very differently distributed, but it is to be regarded as occupying in some measure, however scant, the whole space. In adult organizations, usually the matter is highly concentrated toward the center and very sparsely distributed in the outer part. In the initial stages the distribution is likely to be heterogeneous with less difference between the outer and inner parts. Uniform distribution therefore becomes the most convenient standard of reference, though probably never realized in fact. Table II gives data from which selections may be made at pleasure in forming representative pictures.

The primitive earth-mass, before sifting began, should have included (1) the light gases that later escaped and were never recovered, (2) the planetesimals that temporarily escaped and were later recovered, (3) the nuclear portion that remained under self-control, and (4) minor factors that may be neglected. Let the whole be taken as having a mass about twice that of the present earth, without prejudice to a higher or lower final estimate. It would then, if properly distributed, have a sphere of control of the order of 1,500,000 miles in diameter and a mean density for the whole sphere of about 0.0011 on the air standard, or, let us say, approximately 1/1,000 of the density of the air at sea-level. As loss by sifting went on the sphere of control should have shrunk to a minimum, after which, when planetesimal accretion began to

overmatch the molecular escape, it should have grown to its present size. It is not best just yet to try to decide what this minimum may have been, but let it be placed as low as $\frac{1}{10}$ of the present mass of the earth to make the gap between our two pictures wide. Its sphere of control would then have approached 500,000 miles in diameter and the mean density for the whole sphere .0011, on the air standard. The spheres of control are here computed on the supposition that the matter in each case is distributed in spherical form and that each concentric layer is homogeneous. Actual spheres of control are not strictly spherical and the distribution of matter at least in the early stages was probably not homogeneous. The figures given are themselves only convenient approximations, but they serve well enough to indicate the general order of tenuity. Only gravitative attraction is taken into account. The phenomena of comets' heads imply that there is a supplementary force in such very diffuse bodies, perhaps electromagnetic, but that may be regarded as merely a "margin of safety" in this discussion.

Among the points to be noted, though they cannot be discussed here, are: (1) the high degree of tenuity, which gives some notion of the extent to which matter may control itself in the terrestrial part of the solar domain; (2) the temperature produced by the expansion of the solar gases to this degree of tenuity; (3) the facilities for radiation afforded by this tenuity; (4) the nature of the internal movements in such tenuous bodies.

I. *The motions inherited from the solar eruption and their co-operation with convection in modifying the condensation of the nuclei.*— The gaseous matter erupted from the sun inevitably carried into its new activities some measure of the turbulence that previously affected it, while the forces of ejection added to this their own differential impulses. In so far as these impulses had uniform effects on all parts of the erupted mass, they merely served to send the whole out into its orbital course. This does not specially concern us here, but we may note in passing that the uniform increments of motion discovered by Pettit in the solar eruptions of May 29 and July 15, 1919, seem to be singularly felicitous factors in promoting projection into orbits without those high tendencies

to dispersion naturally assigned to simple explosion and that would be unfavorable to self-control.[1] We are here concerned only with those differential impulses that affected the relations of one part of an ejected mass to other parts. It is assumed that these differential impulses were so graded that (1) they scattered into planetesimals a notable part of the projected mass, (2) they tore away from the central portions segments that were massive enough to hold themselves together, but not very firmly, while (3) the main central masses retained a higher degree of self-control.[2] Such a partition of effects seems the natural result of the mechanics of eruption. It seems also to fit the requirements of the bodies that now make up the planetary system. The masses that retained their self-control were the nuclei of the organizations that were to follow, and constitute the theme to which we are here confined.

Under such a range of impulses the nuclei probably graded from the largest and most strongly held down to small diffuse ones on the very limit of self-control, beyond which complete dissipation into planetesimals set in. They are therefore to be dealt with as a graded series rather than a single type. The question of control, however, was not so much a matter of mass as of balance between the force of gravity and of the motions involved.

Three types of inherited motions need recognition: the turbulent, the vortical, and the rotatory. Turbulent motions were not only inherited directly from the sun, but must have been generated by unbalanced thrusts and drags incident to eruption. Eruptive actions almost inevitably give rise to more or less of vortical motion, or at least some form of eversive motion. In free interplanetary space, and in such tenuous bodies as those under discussion, motions of this type might persist long and be specially effective in discharging internal heat. All unbalanced differences of thrust and drag in the ejection of erupted masses would ultimately appear in the form of rotation and so rotation of some order could scarcely have failed

[1] *Jour. Geol.*, Vol. XXVIII (February–March, 1920), pp. 145–49, or the original article by Pettit, *Astrophys. Jour.*, Vol. L (October, 1919), pp. 206–19.

[2] In addition, the least projected parts fell back to the sun, while doubtless some particular parts received cumulative impulses and were thrown into anomalous courses, but these are neglected throughout this discussion.

to be inherited from the ejection. The amount of this primitive rotation, however, is not deducible directly from such rotations as the bodies now have, for the present rotations are assignable chiefly to the effects of planetesimal infall after the nuclei had become planetary cores. This later effect was conformable to a law of equilibrium under which the rotations were sometimes accelerated and sometimes retarded.[1]

When these inherited motions were strong enough to cause dissipation, the nuclei of course vanished into planetesimals, but when they were mild enough to be consistent with control, they became vital factors in the process of concentration. The normal system of thermal convection was gradually developed later and hence had to conform to the inherited motions already in control of the matter. In large nuclei the convectional motions might come in time to dominate the inherited motions, but in the smaller diffuse nuclei that were more quickly cooled it perhaps never came to be more than a secondary factor. At any rate, the dependence of the convective circulation on the inherited motions—merged mainly into rotation later—must have given rise to a distinctly gyratory system of circulation. This doubtless had some analogies with the circulations of the atmosphere and of the ocean, which, though essentially thermal, are profoundly affected by the earth's rotation. A fundamental difference, however, needs notice. We are here dealing with hot bodies whose radiation is primary. The surface of a rotating body has its greatest convexity transverse to the equator, while the polar surfaces are relatively flat. The greatest radiation in proportion to the immediate submass therefore takes place in the equatorial region. In addition to this the escape of molecules is aided by the centrifugal component of rotation, which is greatest at the equator and sinks to zero at the poles.

It has already been noted that escaping molecules carry off thermal energy in relatively high amounts. The escape of molecules may then be regarded as a form of quasi-radiation. It is, therefore, a rather firm inference that the equatorial belt is the most effective cooling tract of a hot, rotating body, though this may easily be masked by the high radiation from all surfaces.

[1] *The Origin of the Earth* (1916), p. 99.

It is a notable fact that the equatorial belts of the sun, Jupiter, and Saturn rotate faster than portions of their surfaces on the same meridian in higher latitudes. This has been the subject of much speculation and has received different explanations, more than one of which may contain a measure of truth. One suggestion is that it is due to the infall of planetesimal matter. A closely allied suggestion is that it is due to the falling back of matter ejected from the sun into the planetary regions and drawn forward in the direction of their motion, so that on returning it carries surplus momentum acquired from the planets. These are not inconsistent with the suggestion here made that part of the acceleration may be merely a phase of circulation normally set up in such hot rotating gaseous bodies. In a hot fluid body of the volume and rate of rotation of the earth, a mass, cooling and sinking from the equatorial surface, would—if it were free from contacts with surrounding matter—acquire an orbital velocity before it reached the center, and hence would sink no farther because the centrifugal component of its motion would wholly offset the pull of gravity upon it. If forced below that depth, its centrifugal component would act as a buoyant force. Of course, the sinking mass never would be free from contacts, and so it would necessarily exchange energies with the contact matter. The sinking mass would thus act as an accelerating undertow for any matter that flowed in above it as it sank; so also it would tend to drag forward whatever was in contact with it on its sides and below. It is not difficult to work out a system of circulation actuated by such equatorial cooling and sinking. It would, however, undoubtedly be subordinate to the intimate turbulence that would spring from other factors. The axial tract would present a unique problem, for it would be little affected by rotation and would not directly be reached by the descending equatorial currents, for they would be restrained by the centrifugal component of rotation and turned northward and southward, completing their circuits by return from the higher latitudes with such deflections as rotation imposed. This part of the circulation may be pictured as two vortex rings made up of spiral submovements trending downward on their contact sides at the equator and upward on their poleward sides. The axial tracts in themselves

would seem to invite a more direct and simple convection, but they might be specially subject to influence from the inherited motions. For example, if the rotation were west-east, like the sun's rotation in which the mass participated before ejection, and there were a north-south axial movement as in the case of the eruptions of May 29 and July 15, 1919, cited above, there might naturally be inherited from this an axial movement from one pole through the center to the other. The original tenuous state would apparently be favorable to this, and, once established, it might be perpetuated as an effective form of central convection. A special interest attaches to this from its possible influence on the solid core as that gradually formed—but this cannot be discussed here.

The point to be emphasized is the inevitable subordination—in the early formative stages—of the convection actuated by difference of temperature to the inherited motions. The circulation, far from being simple descent and ascent, was tortuous and involved, and the core-forming process must be interpreted on this basis.

II. *The molecular sifting of the nuclei required to reduce the original solar gases to the composition of the present solid bodies.*—The nuclei of the giant planets may be passed by, merely remarking that there is little reason to think they suffered much sifting; rather they seem to have been so massive from the outset that they retained all classes of molecules that came under their control. By far the larger number of the solid bodies of the solar system, however, are practically devoid of free gases, and seem to be formed almost wholly of stony and metallic matter. None of the terrestrial planets carry more than a very small percentage of free gases; apparently almost their whole substance consists of stony and metallic materials such as make up the main body of the earth and of meteorites.

The original gases of all the bodies derived from the sun, large and small alike, should have had essentially the same composition. Spectroscopic analysis shows that the visible substance of the sun is an intimate mixture of many kinds of molecules. Unfortunately, their relative proportions can merely be inferred in a general way. The low density of the sun (1.40), notwithstanding its great mass, implies—even when its high temperature is considered—

that the lighter elements form a notable factor, and the spectroscopic evidence tallies with this. The low densities of the giant planets derived from the sun (Jupiter, 1.25; Saturn, 0.63; Uranus, 1.44; Neptune, 1.09) suggest a similar constitution with even more cogency, for they are much less affected by high temperature. If, therefore, solid stony or metallic bodies of high specific gravity were to be formed from outbursts of solar gases, the process must have involved the removal of large quantities of the lighter order of constituents. This sifting is precisely what the kinetic theory of gases applied to small bodies would lead us to expect. The process is essentially a form of evaporation, and so the planetoids and satellites, as well as the terrestrial planets with slight qualification, may be regarded *as merely the residues of the selective evaporation of much larger original bodies of mixed gases.*

If the original gases, after they were projected from the sun, occupied some large part of the spheres they could control, as indicated above, the escape of the lighter molecules would be relatively easy and prompt, at least from the smaller masses. If the nuclei became much condensed before the sifting was completed, the remaining escape might be slow, for the molecules could then only escape from the outer zone where free paths were open to them when they chanced to rebound in an outward direction with the requisite velocity. In so far as the original gaseous masses were affected by turbulence, or by vortical or other eversive motions derived from their ejection, the escape of the light molecules would be facilitated.

The motions inherited from the original expulsion were probably such that the dominant tendency, in all but the more massive nuclei, was toward gaseous dispersion. Not only would the light molecules be likely to escape from control, but many of all kinds. This is only another form of stating the primary tenet of the planetesimal hypothesis, viz., that such dispersion was an inevitable effect of the solar eruptions, and a condition precedent to planetesimal accretion later. There is merely the reservation that enough material was held under self-control to serve as collecting centers of the requisite orders of efficiency, but even this is not essential to an ultra type of planetesimal genesis. It seems, how-

ever, to be definitely implied by a posteriori reasoning from the existing bodies. The present line of attack shows that the nuclei, except the four of the giant order, were little more than the residues of the heavier material left by selective molecular action working on larger original bodies of mixed gases. This seems to apply to all satellites, to all planetoids, and, in qualified degrees, to all planets from the earth downward.

The process of evaporation had the effect of reducing the energy of the residue per unit mass, and this, added to the inevitable loss by radiation, made control increasingly secure and caused loss to diminish till it became negligible.

III. *The formation of precipitates and of Brownian mixtures, grading into quasi-gaseous clouds of precipitate aggregates.*—As the original mixed gases emerged from the sun, expansion, abetted by radiation, must have promptly lowered the temperature, and this lowering of temperature doubtless led to the formation of precipitates. It is immaterial just here whether these precipitates were formed by simple cooling or by chemical action, or by both acting jointly. Nor is it of critical importance whether the precipitated particles were liquid or solid. It is highly probable that the earliest precipitates were formed of material such as later became the stony and metallic substances of the earth, of meteorites, and probably of all the small solid bodies. That such precipitates had begun to form even earlier is highly probable, for they are apparently now forming in the sun; at least the solar photosphere is commonly interpreted as a cloudlike zone of such precipitates.

At the outset such precipitates would necessarily be minute and diffusely scattered, for under the law of diffusion of gases the particular molecules that were precipitable at the temperatures existent at that particular stage would be distributed sub-uniformly throughout the turbulent mixture of molecules which formed the gaseous mass, but aggregation into granules, chondrules,[1] or other forms of concretions would doubtless at once ensue, after the analogy of the droplets and crystals of clouds.

[1] I venture to name chondrules here to suggest that conditions such as these are perhaps those most likely to have given rise to these singular little aggregates found in the majority of meteorites. They are commonly of the size of a millet seed, but range up to that of a walnut and down to dustlike fineness.

The minute precipitates thus scattered through the gas would serve as Brownian particles, and the increase of these would form a progressive series of Brownian mixtures. The minute precipitates would be jostled to and fro much as the free molecules were, except that, on account of their greater sizes and masses, they must have responded rather to combined molecular impacts than to single ones, while their lack of perfect elasticity must also have somewhat toned down these activities.

An analysis of the conditions makes it clear that the Brownian evolution probably diverged very soon into two rather distinct lines, though they must have been united by numerous intermediate phases. One of these may be regarded as the typal line of gaseous descent; the other as divergent toward an alien type that combined a quasi-gaseous phase with a partially orbital factor. In the first the characteristic feature continued throughout to be that of a jostling assemblage, though the original high proportion of molecules gave place more and more to precipitates acting as Brownian particles. The gas in this case is presumed to have passed into the liquid phase and thence into the solid form. In the more divergent line the assemblage lost its free molecules largely, and in the extreme cases entirely, and became at best merely quasi-gaseous, with a trend toward orbital behavior. Though truly gaseous at the start, the molecular assemblage soon began to be seriously depleted by the escape of the more active molecules and the passage of the rest into precipitates and thence into aggregates, while these tended to lose their to-and-fro dynamics and take on circulatory, rotatory, or revolutionary dynamics.

Divergent as these trends were, they were readily reversible. When molecules escaped from a nucleus in which their habit was strictly gaseous, they usually took on a specific orbital habit and beame planetesimals; the accident of an encounter, however, might easily throw them back into to-and-fro oscillation. Notwithstanding such reversals, two quite contrasted systems of dynamics arose and were continually contending with one another in the processes that marked the passage of the nuclei into cores.

The gaseous line of descent was obviously dominant in the nuclei of the giant planets. Perhaps it was also in the nuclei of the

earth and of Venus. But just how far down the scale it held its dominance may best be left an open question for the present. The considerations about to be offered imply that the second line of evolution was preponderant in the history of the small nuclei.

In nuclei massive enough and quiescent enough to maintain high internal temperatures it seems probable that the precipitates would generally pass from the gaseous state directly into liquid droplets which would serve for a while as Brownian particles and gradually gather into liquid cores, which in turn would develop solid precipitates within themselves and ultimately collect into solid cores. In following this more typical line of gaseous descent, however, it is important to discard the old view that magmas are melts, and to replace it with the modern view, now well established, that magmas are mutual solutions. There are of course melts, and melts sometimes freeze, and so melting and freezing have some place in geological processes, but it is a rather trivial one compared with solidification by chemical processes. Even on the present surface of the earth, which for a hundred millions of years or more has been developing a temperature contrast between the exterior and the interior, simple refrigeration has little expression except in the form of thin crusts; the interiors of even surface lava flows or pools have solidified chiefly by crystallization brought about by saturation in the mutual solution. In a nucleus so conditioned as to sustain the progressive collection of a liquid core at its center by hot precipitates from enshrouding gases there is little ground for postulating even the trivial crust formation that takes place on lavas poured out on the present cold surface. Superficial refrigeration could scarcely have been more than a negligible process. Appropriate temperatures and pressures must of course have been very essential factors in core formation, but rather as imperative conditioning influences than as direct agencies. They were less intimate and ultimate factors than the chemical forces that served as the immediate actuating agencies.

Unfortunately, present knowledge of the precipitating processes deep within magmas is insufficient to predict with much confidence the history of even an ideal liquid core in a perfectly quiescent state, much less to forecast the solidification of a core actuated by

such a tortuous circulation as the case in hand seems really to involve. Inquiry should, however, at least be put on the right track by recognizing the later aspects of science and the physical realities of the case.

It is at least safe to say that isolated crystals are habitually formed *within* magmas, not merely on their surfaces. In addition to this it is particularly important to recognize that the order of formation of minerals in magmas is not that of their melting-points, but rather singularly at variance with it. Some of the minerals commonly formed earliest, as magnetite, apatite, and ziroon, are higher in specific gravity than the average minerals formed later, and these are generally higher than the liquid from which they were separated. It is quite reasonable to suppose, as leading petrologists do, that the heaviest order of minerals, at any rate, if not the majority formed, would tend to sink through the mutual solution. The actual effectiveness of this tendency must, of course, be dependent on the viscosity of the magmas, the vigor of the circulation, and other conditions. Whether the heavy minerals would remain solid and collect at once at the center or be redissolved in the depths and continue longer in the circulation is doubtless to be left an open question for the present. But this and other questions are to be considered *under the conditions of a tortuous circulation rather than those of a quiescent liquid.* The tendency of the circulation must certainly have been to equalize the temperature and to favor a slowly progressive precipitation affecting large portions, if not all of the mass, rather than the mere surface. The heavier precipitates might then rather plausibly be assumed to collect where the combined effects of current and gravity offered them the most available resting places. If so, a core shaped to fit such conditions seems more probable than a strictly symmetrical sphere.

If we turn now to the other type of nuclear evolution—in which the sifting action not only went to greater lengths, but the sifted residue was much more affected relatively by motions inherited from the expulsory action—it is well to recall at the outset that the range of cases stretches from the largest solid bodies notably affected by the sifting process downward to the very borders of

complete dispersion, such complete dispersion springing variously from inherited motions, from thermal convection, from molecular activity, or from divers combinations of these. If, as the naturalistic method insists, the solid bodies themselves are to be taken as the vestiges of the actual process, the observed range in size tallies with our previous suggestion that the limits which permit success along this line are actually reached in the existing series. Apparently our best method, then, is to consider the whole range for the sake of learning what were the inhibiting conditions at the vanishing end. We may then the better form an opinion of what probably took place nearer the middle of the great series where our interest chiefly lies. A naturalistic method is much to be preferred to a deductive treatment, for the latter is embarrassed by the multitude of possible assumptions. In pursuance of the naturalistic method let us seek some telltale feature that has been actually realized and make that our base of procedure. The series of atmosphereless bodies furnish such a base. They tell us within what bounds the inhibiting limit lay for such gases as form atmospheres. In passing through the actual conditions of evolution they have been stripped of all gases as light and active as nitrogen or oxygen. Further than this, they have maintained that condition since. The conditions must probably have been most exacting in the hot genetic stages, and there has been chance for recovery since. Their present condition, with some reservations, may be taken as an approximate indication of equilibrium conditions. The graded list in Table I giving the range of planets, planetoids, and satellites from the earth down, may be found convenient here.

The case of atmospheric gases being thus approximately determinate, it remains to find at what stages the gases or vapors of such stony and metallic substances as make up the earth, meteorites and like bodies, would encounter their inhibitive limit. The basis for this lies in the fact that the molecular velocities of molecules vary inversely as the square roots of their molecular weights. The heavier we assume the molecules to be the more conservative our conclusions, so let us assume that the small nuclei were composed of molecules as heavy as those of the leading minerals in meteorites. The square roots of the molecular weights of the nine

minerals commonest in meteorites, including iron, are 10, 10.59, 12.49, 14.69, 15.87, 16.18, 16.49, 16.70, 18.38. These are to be compared with the square roots of representative molecules that are not held by the atmosphereless bodies. We may take the molecules of oxygen and nitrogen as representing these, the square roots of their molecular weights being 5.66 and 5.2, respectively. The high temperatures at which alone the stony and metallic substances occur in working quantities enter vitally into the case.[1] Making requisite computations, it appears that these heavier molecules would not be held under genetic conditions by the four lower orders of the bodies given in Table II. This seems to force the conclusion that the planetoids and smaller satellites were not formed in a purely gaseous way. As this is a rather radical conclusion it is well to note that the premises have not been strained to reach this result but quite the opposite. The bodies have been taken at their full present masses, whereas only their nuclei were really involved during the critical genetic stages. The molecules are taken in their present complex state, whereas in their volatile state they were quite possibly simpler and hence more active. The attractive power at the surface of the present cold concentrated bodies was used, whereas the attractions at the surface of the expanded gaseous bodies would be much lower. Other concessions to conservatism were made.

But this only excludes a direct or immediate formation by the gaseous method. It leaves open the question whether or not the cloud of precipitates into which the original mixed gaseous substances naturally passed could have completed the work. If so, the genesis might have lain in the alien line of gaseous descent, though not in that of strict gaseous formation.

It was noted earlier in the discussion that the gases of the stony and metallic substances must have begun to be precipitated soon after expulsion from the sun. In the small detached segments the precipitation must probably have gone on rather rapidly to com-

[1] I am under obligations to Dr. Fred. E. Wright, of the Geophysical Laboratory of the Carnegie Institution of Washington, for information and advice on points involved here, as also to Professor W. D. Harkins, of the University of Chicago. In the statements made I have endeavored to avoid all uncertain ground and leave everywhere a margin of safety.

pletion, and the work of aggregation into granules probably followed closely after. The conditions for the escape of the molecules that remained free would also be favored by the smallness of the bodies and the condensation of the precipitated portion. The escape of the free molecules would leave the precipitate aggregates with such internal motions as were inherited from the previous states. The last previous stage was that of a Brownian mixture whose internal motions did not differ radically from those of true gases, but the growing inelasticity must not be overlooked. The laws that would have governed the cloud of precipitates when first formed would not have differed very widely from gaseous laws. The inherited motions had, however, as we have seen, introduced a tendency toward an orbital development. In general the precipitated particles in a Brownian mixture so conditioned would not fall directly to the center even if an open path were provided for them; on the contrary they would pursue elliptical orbits about the center. By interference they would undoubtedly at length reach the center but only through a delayed course with consequent dissipation of energy.

Now the units—which at the start were perfectly elastic molecules—would by the precipitating and aggregating processes grow into granules many million times more massive, and in the process would become increasingly inelastic. By this change in the nature of the unit there would have arisen a wide gap between even the heaviest of the free molecules and the average spherules, granules, or chondrules into which the precipitates passed. The velocities of the latter would have been of so much lower order that there seem no good grounds to doubt that the main mass of the latter would be susceptible of control and continued concentration under conditions that would be quite prohibitive of control as free molecules.

The very process of molecular escape tended in itself to increase the gap between the units prone to escape and those prone to continue their concentration. In every collision from which a molecule escapes by rebound there is an equal reaction of the partner in collision in the opposite direction. The escaping molecule usually has the lesser mass and to give escape the rebound must

be outward; the reacting molecule or granule therefore rebounds inward. *The very process of dispersion was therefore mated with a concentrating process and the two divided their results between the forming of nuclei on the one hand and of planetesimals on the other.* On the residual side of the twin process the ultimate result was the formation of a cloud of precipitated granules from which all free molecules had escaped. The cloud of course had less mass than the previous mixed nucleus, but there was a proportionately larger reduction of dispersive activity.

In the light of this we need next to consider further the holding power represented by the sphères of control. The spheres of control in Table II are computed for the earth's distance from the sun. They would be relatively larger farther out and smaller farther in. By reference to the table it will be seen that the fields under control are by no means insignificant even for the smallest bodies represented. At the same time, reference to the adjoining columns of the table will show that the *strength* of control is distinctly limited. It is also to be noted that the velocities of retention and escape are given for the surfaces of the concentrated bodies as these now are, and that the velocities that can be controlled decline rapidly for points farther from the center.

Now expansion does not affect the simple static holding power so much as it does the velocity that can be controlled. Within the limits of the sphere of control, and with some other qualifications, simple expansion or contraction does not affect the extent of the sphere of control. It is a principle of celestial mechanics that if a body is spherical and if its substance is distributed either uniformly or in homogeneous concentric layers its gravitative effect on bodies outside it is as though the whole matter were concentrated at the center, and hence, of course, expansion or contraction is immaterial so far as relates to bodies on the borders and outside the body itself. If the body is not strictly spherical or homogeneous in concentric layers, the deduction will not strictly hold, but any departure will in general be measurably in proportion to the departure from sphericity or homogeneity, so that the principle may be used without radical error in respect to normal spheroids of revolution. Applying this deduction to the range of bodies rep-

resented in Table II, the sizes of the spheres of control will remain about as given whether the substance they contain takes the form of an expanded gas, or an open swarm of precipitated granules, or a compact solid body. This puts everyone in the way of modifying at pleasure the illustrations I offer.

To the concrete pictures already given the following may be added as now more immediately serviceable. From the minimum radius of the sphere of control of the earth, 620,000 miles, let a depth of 20,000 miles on the outer border be left essentially unoccupied and the whole present substance of the earth distributed uniformly throughout the remainder. It would have a density of 0.001266 on the air standard. In the form of a cloud of granules, each half the mean density of the earth. and distributed uniformly, the empty space about each granule would be over a million and a half times the space occupied by the granule itself.

If a 10-mile planetoid were converted into a cloud of granules uniformly distributed through its sphere of control. the cloud would have a density of 0.00111 on the air standard. If the granules had the same density as in the planetoid, the average empty space about each granule would be more than two million times the volume of the granule itself.

If therefore the clouds of granules were quite diffuse. they yet might be controlled by their mutual gravity, *provided* the dispersive components of their internal movements were negligible. But with such wide distribution any appreciable dispersive movements would be fatal to control.

To fashion a case of this order with a working margin of space, let the matter of a 10-mile planetoid of density 3.3 be dispersed uniformly as granules of like density throughout the central $\frac{1}{8}$ of its sphere of control, leaving the remaining $\frac{7}{8}$ as empty space which the granules must cross to escape. The density on the air standard would be 0.00889, while the average empty space surrounding each granule would be 280,000 times the volume of the granule itself. Even in this case the velocity at the surface that would give escape if directed outward would be perilously low, not above a fraction of an inch per second. This reveals the critical nature of all this class of cases. To insure success in final concentration, the

sifting process that preceded must have removed all constituents whose motions had any notable dispersing component; nor can any such component arise from mutual interaction without jeopardy. Almost the only line along which a body so small as a 10-mile planetoid could organize itself by the granular method seems to have lain in acquiring very early a higher central density and a less outward extension than that assigned. This might perhaps have been done by the reaction above noted. The peril of dispersion and the narrow margin of control in such cases lead to the conclusion that the smallest order of planetoids and satellites lie near—or perhaps quite on—the limit of possible genesis by even this divergent phase of the gaseous line of descent.

This conclusion tallies with the fact that no planetoids or satellites of the smaller order are known at the earth's distance from the sun, or within it. Bodies of this type appear only at the distance of Mars and beyond. The dynamic conditions of this inner region are perhaps too adverse for this type of formation. In the outer region conditions are notably less restrictive, but even there they undoubtedly put lower limits on the size of bodies formed by the gaseo-granular method of assemblage.

In the light of these considerations there seems little warrant for supposing that such bodies were ever formed in sufficiently great multitudes to have built up the earth or to have pitted the surface of the moon by their impacts. The number of lunar craters is estimated at 30,000. If each of these is the grave of an extinct planetoid, one might expect that a few living ones would have lingered to tell the story. The negative testimony of the heavens as to their existence in this region seems rather to favor the view that their restriction to the outer region implies that they are themselves witnesses to the limitation of this line of genesis in both place and frequency.

With the general lines and limits of nuclear evolution thus defined, our remaining task is to find the median places between the two extremes that fit the earth, Venus, Mars, and the moon. It is clear from the present state of these bodies that much sifting of the original solar gases was required, for while the earth, Venus, and Mars hold envelopes of gases of moderate molecular weight,

they do not hold hydrogen and helium, which abound in the sun in appreciable quantities. The sum total of the gases they do hold relative to the whole mass of these planets is very small. Even in the case of the earth, distinctly the most massive of the solid bodies, the sifting must have gone to very notable lengths.

It is not impossible that the nuclei of all four bodies were so far sifted down as to exclude essentially all the atmospheric gases, and as a result their concentration fell ultimately into the precipitate line of descent. On the other hand, it is quite possible that the earth and Venus had atmospheres of some moment at all stages. In the case of the moon, there seems no escape from the view that its nucleus could not have formed in gaseous fashion, for the moon does not even now hold an atmosphere. In its original hot diffuse state a mass of so low an order as the nucleus of the moon could only hold its material in the precipitate form. The atmosphere of the adult Mars is so scant that its nucleus probably had no appreciable atmosphere. It is doubtful whether Mars could even now, in its full-grown state, hold the atmosphere it has if the planet were heated to the point of volatilizing its stony substances. The cases of Venus and the earth seem so nearly on the border line that it is not unreasonable to take either view as the evidence now stands. Further study may turn the scales one way or the other.

So far as the shrinkage question is concerned, the matter narrows down to the possibility that the nuclei of the earth and Venus passed from their original gaseous states into planetary cores along the normal line of gaseous descent. If the main mass of the nucleus of the earth passed from the solar gaseous state into a central liquid magma and thence by chemico-crystalline action into a solid core, the process would have given special facilities for the adjustment of the matter in the interest of density. To that extent it would have forestalled later shrinkage that might otherwise have been recorded in diastrophic features. The *record* would not cover the full reality. The large amount of shrinkage deduced by our comparison of the moon, Mars, Venus, and the earth[1] would not be recorded even in the basal features of the earth's configuration. These studies, however, imply that the unrecorded

[1] *Jour. Geol.*, Vol. XXVIII (1920), pp. 1–17.

factor was not necessarily large relatively, even if the gaseo-molten phase of nuclear history did obtain and is given as generous an estimate as the data will warrant.

It ought not to be overlooked, however, that the solid core, in its assigned formation by the deposition of crystals or other precipitates from the gyrating currents of the central circulation, would have been very likely to have incorporated inequalities of material and taken on asymmetries of form so as to have presented a deformed foundation, as it were, for the later accretions. Such deformities would have been likely to have made themselves felt in the diastrophism of all that was built upon them. This is a phase of the subject which I hope to pursue further in the future.

IV. EXTERIOR AGENCIES THAT AFFECTED THE PLANETARY CORES DURING THEIR FORMATION AND AFTERWARD

The discussion thus far has been confined to agencies acting within the evolving masses. The evolution, however, was not free from influences that acted from without. One type of such action particularly requires consideration here, because it affected the successive adjustments and readjustments of material in the planetary cores. It will suffice to consider merely the case of the earth and the most typical agencies that affected it. The three agencies that lie back of changes of rotation, of nutation, and of the tides will sufficiently represent the whole. These agencies—and those of their kind here neglected—arose out of the same general processes as the planetary series itself and came gradually into function as the planets themselves took form. They were more or less effective at all stages thereafter. One special effect was to bring into play the resources that lay in the *mass-coherence* of solids, an essentially new element in the evolution.

The forces that produced the tides, the polar nutations and the changes in rate of rotation, not only caused changes of form that involved variations in the internal capacity of such inclosed spaces as there may have been, but caused differential stresses to permeate the growing cores from surface to center and call into action the viselike capabilities of stresses greater below than above. Those agencies which give rise to deformations of the

class known as zonal harmonics of the second order, such as the bulging of an equator and flattening of the poles, or the pulling out of polar cones and the flattening of the equatorial belt between, give rise to stresses much greater in the central parts than in the outer parts. Sir George Darwin[1] and others have computed these for an incompressible homogeneous earth and for certain compressible variations from this. In an incompressible homogeneous earth Darwin gives the differential stresses as bearing the ratios 8 at the center, 3 at the equatorial surface, and 1 at the poles. In a compressible earth the surficial stresses are relatively lower and those at the center relatively higher. For a certain compressibility the surficial stresses disappear and the central stresses rise $\frac{1}{6}$ in value.[2]

Now the main tidal stresses come and go every twelve hours and the subordinate tidal stresses at other and generally longer intervals. While relatively small, they are constantly acting in a given direction, and this presumably has a certain kind of cumulative effect. This effect is doubtless chiefly felt by such molecules of the interior as are under stress and are about ready to change their attachments and so are responsive to the influence of even small strains. It is coming to be recognized that such individual molecular activities constitute a notable factor in rock metamorphism, glacial motion, and other geological changes of a very intimate sort. This has been set forth by Leith[3] and other close students of the intimate nature of geological phenomena. Such persistent rhythmical oscillations of stress and strain as those of the tides seem well suited to aid effectually these individual molecular changes. The nutations of the poles represent pulsatory action whose periods are longer, but whose chief effects are probably of the same intimate sort.

Changes of rotation, however, represent action of a much higher order of power and much greater length of period. In deformative potency, rotation has a competency of the first order. Changes of rate of rotation were probably most active and effective while

[1] *Scientific Papers*, by Sir George Darwin, Vol. II (1908), pp. 476–81.

[2] *Ibid.*, p. 505.

[3] Leith and Mead, *Metamorphic Geology* (1905), pp. 173–76, and elsewhere.

planetesimal accretion was in progress. The earth core was then youngest and least compressed, and so probably least rigid and most susceptible to the influence of differential stresses. I have elsewhere shown that the changes in rotation were probably oscillatory about a medial rate in conformity to a law of equilibrium.[1] They may be regarded therefore as commanding influences both in respect to power and to the times and modes of application.

The elevated poles and depressed equator of the rhythmical tidal deformations were transverse to the elevated equator and depressed poles of the rotational changes, and this transverse attitude no doubt lent facility to the kneading action which their rhythmical periods brought to bear on the interior of the earth.

These co-operating agencies thus brought to bear on the whole interior of the solidifying earth a rhythmical series of differential stresses, most intense in the deeper parts and less intense toward the surface, and so admirably fitted to force the mobile and the lighter material toward the surface and to favor readjustments that brought about increased density and rigidity and probably also increased elasticity. It seems to me probable that this combination of strong mechanical stresses at distant intervals working with much gentler and more rapid rhythmical stresses has been the master-factor in controlling the secular reorganization of the earth's interior, a gradual reorganization which I think has been in progress from the time solidification began down to the present day. The normal result, as I see it, would be a general gradation of concentrative effects from surface to center—taking form in appropriate gradations of density, rigidity, and elasticity, also graded from surface to center. The results of our comparative study of the earth, moon, Mars, and Venus tally perfectly with this view and make it theoretically logical and consistent. The steadily increasing density from smaller body to larger body, in spite of the high probability that the smaller bodies inherited the heavier molecules, points very definitely to reorganization under the influence of compression. The oscillating differential stresses, greater below than above, seem peculiarly well suited to aid in working out the graded adjustments.

[1] *The Origin of the Earth* (1916), pp. 95–110, 172–79.

The cumulative evidences of recent investigations on tidal, seismic, nutational, and other phenomena support this view with little less than demonstrative effect. The most of these are now quite familiar. There is space here merely to quote the latest numerical determinations (1917) that have come to my notice. Schweydar,[1] as the result of observational, experimental, and mathematical work on the tides, the polar nutations, and the transmission of seismic waves, concludes that the earth conducts itself as though it had a mean rigidity $2\frac{1}{2}$ times that of steel, that the constant of rigidity at the surface is about 3×10^{11} dynes, that this increases in depth more rapidly than the density, so that at the center it reaches 30×10^{11} dynes, or ten times its value at the surface. The transverse seismic waves, as far down as the record permits a confident interpretation, indicate a definite gradation of density, rigidity, and elasticity. To insure that the total rigidity shall reach the mean value of $2\frac{1}{2}$ times steel, and at the same time be consistent with the rigidity known to prevail in the outer zone and the gradually rising rigidity implied by seismic waves as far down as their record is good, it seems clear that a high order of rigidity in the remaining central part is imperative. The old hypothesis of an iron core framed, among other reasons, to account for the high mean density of the earth—a purpose which it serves only clumsily—does not help much in meeting the still higher rate of rise of rigidity and elasticity toward the center, for iron is soft and malleable when hot. Nor does any special segregation of inherently heavy material in the earth, however helpful it may be in its place, fully satisfy the phenomena brought out by the comparative studies on the earth, the moon, Mars, and Venus. The whole evidence seems to point clearly to a systematic mass-effect, working on essentially the same material in all cases, aided, to be sure, but aided in only minor degree, by selective segregation. In the heart of the earth very likely the segregation of the metallic from the stony material has gone much farther than in the outer parts, but I see little reason to think the two classes of material have been wholly separated from one another. A segregation

[1] W. Schweydar, "Ueber die Elastizität der Erde," Sonderabdruck aus *Die Naturwissenschaften* (1917), pp. 1–27.

of the iron and allied metals into masses of moderate dimensions distributed through the stony material, after the fashion of the metallic and stony material in meteorites, would probably affect appreciably the transmission of transverse seismic waves, and so account for the peculiarities of the record of such waves as come through the heart of the earth quite as well as the assumption of a purely metallic core. An original mixed constitution from center to surface kneaded into the present solidity by differential stresses whose central intensity is to their surface intensity in about the same ratio as the central density, rigidity, and elasticity is to the surface density, rigidity, and elasticity seems to fit the requirements of the case.

NOTES ON THE MECHANICS OF GEOLOGIC STRUCTURES

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INTRODUCTION

Since an early date in the development of the science of geology it has been recognized that secondary structural features are the results of failure or yielding of rocks under deformative forces, and students of geology have attempted to interpret these secondary features in terms of the forces and movements which produced them. Because of the great size and heterogeneity of the earth masses involved, the analysis of the casual mechanics of a given major structural feature is never a simple matter. The geologist, not having witnessed the production of the structural features at hand, or of any similar features, finds it difficult to view the problem in perspective and in proper relationship to associated structural features.

Discussions of the mechanics of deformation in geologic literature on the whole indicate a rather elementary conception of the factors involved and a tendency to assume more or less arbitrarily a simple set of mechanical conditions, when the structures observed may be susceptible of several alternative explanations. A single structural feature or group of similar features is not necessarily indicative of the type of deformation involved. A group of intersecting faults may be looked upon as a sequence of unrelated events, when, with equal or better reason, they might be considered as essentially simultaneous and due to a single deformation. The two interpretations require a widely differing structural history of the region involved.

An open fissure obviously due to tensional stresses (so far as the fissure itself is concerned) may be an incident in simple elongation, shear, cross-bending, compression or shortening, or torsional

warping. A reverse fault implies conditions of shortening or compression but may in addition to this possibly be an incident in a general shearing movement, or a phenomenon of simple cross-bending, or may be due to torsional warping. A series of folds may be due to shortening or compression in a direction normal to the trend of the folds or to a general shearing movement in a direction at a considerable angle to the trend. In general the shearing type of deformation has been largely neglected in analyses of the mechanics of geologic structures, both fractures and folds.

It is in part the purpose of this paper to present the result of experimental work which illustrates the variety of mechanical explanations possible for a given structure, and incidentally to emphasize the extent to which many of these may be related to shearing, which the writer regards as an exceedingly common type of deformation in rock movements. It is further purposed to present and to illustrate experimentally analyses of the stresses involved in the various types of deformation.

DESCRIPTION OF APPARATUS

Several years ago the writer devised for use in the structural geology laboratory of the University of Wisconsin a simple type of apparatus for studying and demonstrating relations of fractures and of folds to the forces producing them. The apparatus is used in three forms as illustrated in Figures 1, 2, and 4. These are similar in construction, consisting of a rigid rectangular frame of gas pipe supporting two clamps between which a heavy sheet of rubber is stretched. One or both clamps may be moved in various ways by means of screws so that tension, compression, torsion, and shear, or combinations of these may be produced in the rubber sheet.

The medium in which fractures are produced is a thin coating of paraffin applied to the upper surface of the tightly stretched rubber sheet and chilled until it is brittle. The paraffin coat is best applied by pouring the melted paraffin very rapidly and freely over the rubber sheet, which has previously been warmed practically to the melting-point of the paraffin. The hot paraffin is allowed to drain from the rubber. A little experience soon

enables one to judge of the manipulation necessary to secure the thickness desired. The chilling can be accomplished by allowing cold tap water to flow over the uncoated side of the rubber. If chilled too rapidly or too much, cooling cracks will develop in the paraffin. Deformation of the rubber sheet produces systematic fractures in the paraffin bearing definite relations to the manner of deformation.

Folds are produced by coating the paraffin with a thin layer of plastic wax and laying smoothly over this a very thin sheet of rubber, such as is used by dentists, or a sheet of tinfoil. When the rubber thus coated is deformed, folds are developed in the plastic wax and its coating, as described later.

This type of apparatus has an advantage over the deformation of large masses of material in a compression machine of the piston type, as the forces are transmitted through the rubber and therefore applied at every point in the coating. The thin coat of paraffin may be considered as representing the flat-lying rocks in the zone of fracture, having wide lateral extent as compared with thickness. The sheet of rubber might correspond to the deeper zone of rock flowage. Deformation of the paraffin-coated rubber is comparable to deformation affecting the zone of flow and the overlying zone of fracture simultaneously. A distribution of stresses throughout the deformed mass is obtained. The phenomena of repeated faults or extensive systematic joining and of repeated folds much more closely simulate nature than do the single fractures obtained in a testing machine or the single folds which develop ahead of the piston in the type of apparatus employed by Willis and others.

An apparatus employing a stretched rubber sheet on which plastic layers were built up and deformed by the contraction of the rubber was employed by Alphonse Favre[1] in connection with a study of rock deformation. In order to apply the compressive force he attached wooden blocks to the rubber to serve as buttresses or thrust blocks. The net result was not essentially different from the results obtained by later investigaters employing apparatus of

[1] Alphonse Favre, *Archives des Sciences Physiques et Naturelles*, Nouv. Pér., Tome 62 (Genéve, 1878), pp. 193–211.

the type used by Willis. A slight modification of the apparatus of Favre was used by Hans Schardt,[1] who used various combinations of plastic and brittle layers in his studies of the mechanics of mountain building. Still another modification of Favre's work was employed by Stanislas Meunier,[2] who studied and described the fractures produced in a layer of partially set plaster on a contracting rubber sheet. These three investigaters confined their work to pure shortening and paid no attention to stresses set up by tension, shear, or warping.

FIG. 1.—Fractures produced by tension. A heavy sheet of rubber is held between two clamps and stretched by means of the screw at the end. It is then coated with paraffin which is allowed to chill until brittle, after which the rubber is further stretched by means of the screw, developing tension cracks in the paraffin.

EXPERIMENTAL RESULTS

Fractures produced by tension.—The apparatus (Fig. 1) consists of a frame with a rigidly attached clamp at one end and a movable clamp at the other which may be moved toward or away from the stationary clamp by means of a long screw. To develop tension fractures the rubber sheet fastened at its edges in the two clamps is tightly stretched by means of the screw and then coated with paraffin which is allowed to chill until brittle. Tension is then applied by further stretching of the rubber by means of the screw. A typical set of tension fractures thus developed is shown in Figure 1.

[1] Hans Schardt, "Études géologiques sur le Pays-d'Enhaut Vaudois." Troisiéme partie. A. Mécanisme des Dislocations. Chapitres xv–xvii. Planches VI–IX. *Bulletin de la Soc. Vandoise des Sciences naturelles*, Vol. XX, No. 90, 1884.

[2] Stanislas Meunier, *La Géologie Experimentale* (Paris, 1899), p. 299.

These are approximately at right angles to the direction of movement as is to be expected. They are open cracks perpendicular to the rubber sheet. These results are what an analysis of the mechanics involved would indicate. The paraffin, like rock, is less resistant to tensional stresses than to shearing stresses. It fails, therefore, by the development of breaks along planes which are perpendicular to the maximum stress.

Fractures produced by compression.—The apparatus used for this purpose is the same as the one employed for tension. The compressive force is applied by releasing the screw and allowing the rubber to contract. This develops compressional stresses in the paraffin coat. The first breaks to appear are small inclined thrust faults striking at right angles to the direction of shortening and dipping approximately 45° either way. (See Figures 2 and 3.) These are followed by small number of vertical faults which strike at angles approximately 45° to the direction of shortening (seen near the margin of the rubber sheet in Figure 2) and are due to the fact that lateral relief is afforded at these points by the "spread" of the rubber sheet. There also appear a number of vertical tension joints striking in the direction of shortening and apparently due also to the "spread" of the rubber.

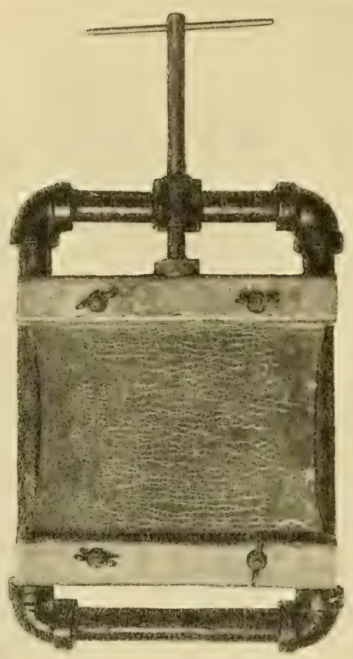

FIG. 2.—Fractures and faults developed by shortening or compression. This is the same apparatus as shown in Figure 1. The heavy sheet of rubber is first tightly stretched by means of the screw, coated with paraffin which is made brittle by chilling, after which the rubber sheet is allowed to contract by means of the screw, thus producing compressional stresses in the paraffin. Figure 3 shows these compression fractures in detail.

An analysis of the mechanics involved leads to conclusions in accordance with the foregoing experimental results. Under simple compression, fracture takes place by breaks which develop in the planes of maximum shear.[1] Therefore the paraffin should fracture along planes inclined at approximately 45° to the direction of the compressive force. The development of these inclined shear fractures requires actual displacement on the plane of fracture.

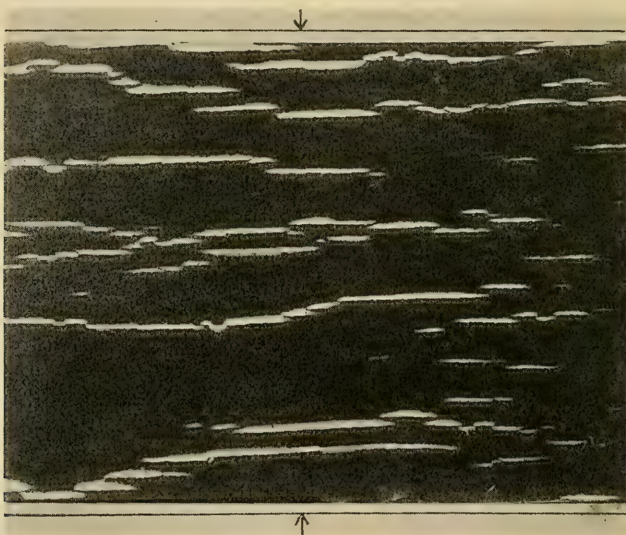

FIG. 3.—Fractures and thrust faults produced by shortening or compression in the direction of the arrows. (See Fig. 2.) The white bands are fractures and thrust faults in the paraffin which strike at right angles to the direction of shortening and dip at angles of approximately 45° in either direction.

This movement has a component parallel to the compressive force and also one at right angles to this force. Evidently, therefore, fractures can develop only in such an attitude as permits this movement to occur. In the central part of the rubber sheet the direction of easiest relief is upward or away from the surface of the rubber and therefore we expect inclined fracture planes striking at right angles to the direction of compression. Near the margin of the rubber sheet lateral relief is afforded, and we find

[1] C. K. Leith, *Structural Geology*, p. 16.

vertical fracture planes striking at angles of approximately 45° to the direction of compressive force.

This experiment in terms of earth movements is to be compared with a tangential shortening of an earth mass extending down into the zone of flowage, accompanied by side flowage or spread. This shortening is communicated to the rocks in the zone of fracture, resulting in inclined thrust faults striking normal to the direction

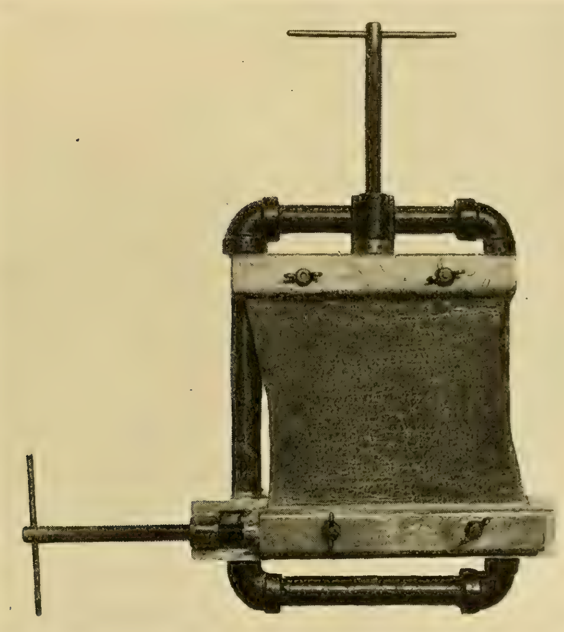

FIG. 4.—Fractures and faults developed by shear or rotational stress. A heavy sheet of rubber is tightly stretched between the two clamps by means of the screw at the top and coated with a thin coat of paraffin which is made brittle by chilling. The paraffin-coated rubber sheet is then deformed by means of the screw at the left. The fractures developed by the shearing movement are shown in detail in Figure 5.

of shortening, vertical shear faults striking at angles of approximately 45° to the direction of shortening and vertical tension joints striking in the direction of shortening.

Fractures produced by shear or rotational stress.—The apparatus used for this purpose is shown in Figure 4. It has one clamp

which may be moved toward or away from the other by means of a screw. The other clamp is mounted in a slide and by means of the second screw may be moved at right angles to the direction of movement of the first clamp. The sheet of rubber is tightly stretched between the two clamps, coated with paraffin, and deformed by means of the screw attached to the sliding clamp. This subjects the rubber sheet and its coat of paraffin to a shearing or rotational stress. The resulting fractures in the paraffin are shown in Figure 5. The direction of movement is indicated by the arrows and the amount of movement by the shape of the parallelogram which was, previous to deformation, rectangular.

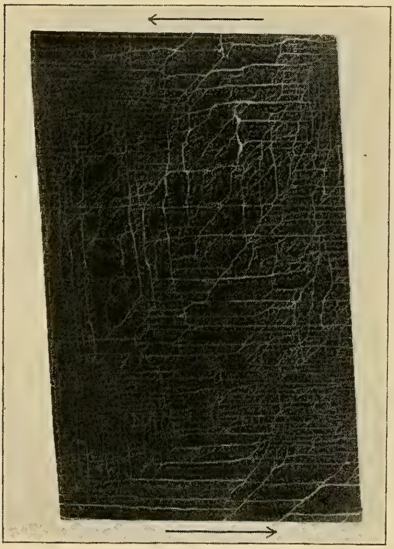

FIG. 5.—Fractures produced in paraffin coat on rubber sheet by shearing. The arrows indicate the direction of movement and the shape of the figure shows the amount of distortion.

The first fractures to appear in any one locality on the rubber sheet are usually tension cracks inclined about 45° to the direction of the shearing movement. These are at right angles to the direction of maximum elongation and appear as vertical open cracks. They are followed immediately by two sets of vertical faults with horizontal displacement, one set striking parallel to the direction of movement and the other parallel to the free edges of the rubber sheet. These represent two directions of non-distortion or two shear planes developed by the shearing movement in which direction of relief is in the plane of the paraffin layer. Another set of faults, only two of which are shown in Figure 5, are thrust faults striking approximately at right angles to the tension crack and inclined approximately 45° dipping in either direction. These are due to

compression in a direction at right angles to the direction of maximum elongation.

The pattern of fractures developed in a series of experiments with varying thickness of paraffin coat is uniform in so far that the foregoing described set of fractures are always found. Their relative prominence, however, varies with the thickness and brittleness of the paraffin coat.

Fractures produced by torsional warping.—It is difficult to form any estimate of the importance of this type of deformation, but it seems probable that torsional warping occurs and, therefore, that it merits consideration as one of the types of earth deformation.

A warped surface may be considered as having been deformed in two manners; namely, by the change in area which has engendered tensional or compressional stresses or both and by bending which has occasioned stresses characteristic of cross-bending. For purposes of the present analysis it appears best to consider these two phases of deformation independently.

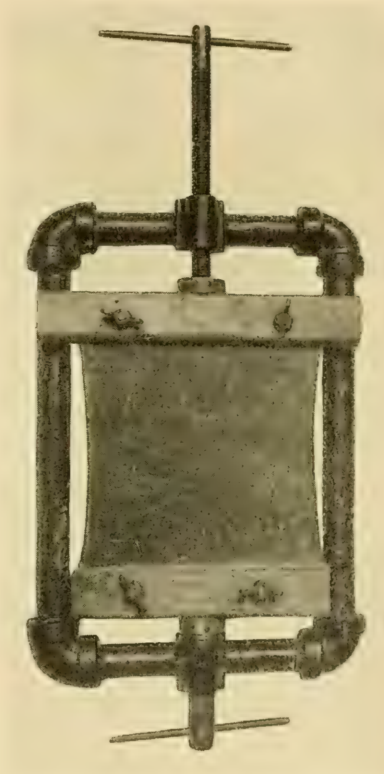

FIG. 6.—Fractures produced by torsional warping. A heavy sheet of rubber is tightly stretched between the two clamps by means of the screw, and coated with paraffin which is made brittle by chilling. Then the lower clamp is rotated by means of the handle at the lower end. This subjects the rubber sheet to torsional deformation and develops cracks in the paraffin. (See Fig. 7.)

Changes in area due to warping.—If a sheet of rubber is held between two clamps, as in Figure 6, and subjected to torsion by turning one of the clamps (maintaining a constant distance between the clamps) the effect is to increase the area of the rubber

sheet. Plainly the center line of the rubber (the axis of torsion) remains unchanged in length, but the lateral margins are stretched, because the rotating of one clamp increases the distance between the ends of the two clamps. This stretching is maximum at the free edges of the rubber and decreases toward the center. The effect of tension thus developed is illustrated in Figure 7, which shows the cracks developed in the paraffin layer as a result of torsional warping of the rubber. Distribution of the cracks shows plainly

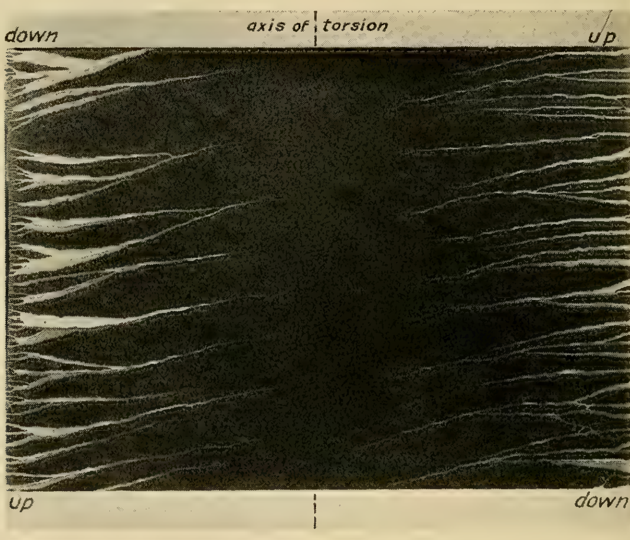

FIG. 7.—Fractures produced in paraffin coat on rubber sheet by torsional warping. (See Fig. 6 and 10C.)

the increase in the amount of tension as the margin is approached. The confluent nature of the cracks, resulting in a minimum number of free ends, is an interesting feature.

The rubber sheet may be so arranged that the free edges remain constant in length during torsion. If the rubber sheet thus mounted is subjected to torsion, there can be no change in the lateral margins. There is a change, however, along the center line because the turnable clamp approaches the other as it is turned, thus causing shortening or compression along the center line. This compression is maximum along the center line and decreases to zero at the edges. A paraffin coat on the rubber

sheet thus deformed develops characteristic overthrust faults of the type shown in Figure 3, which are most numerous along the center line and decrease in abundance and displacement toward the margin.

We have in these two types of deformation limiting cases, neither of which is probably realized under natural conditions. In the first case there is a net increase in area; in the second case a decrease in area. We may now consider an intermediate case in which the total area remains constant. This in terms of the

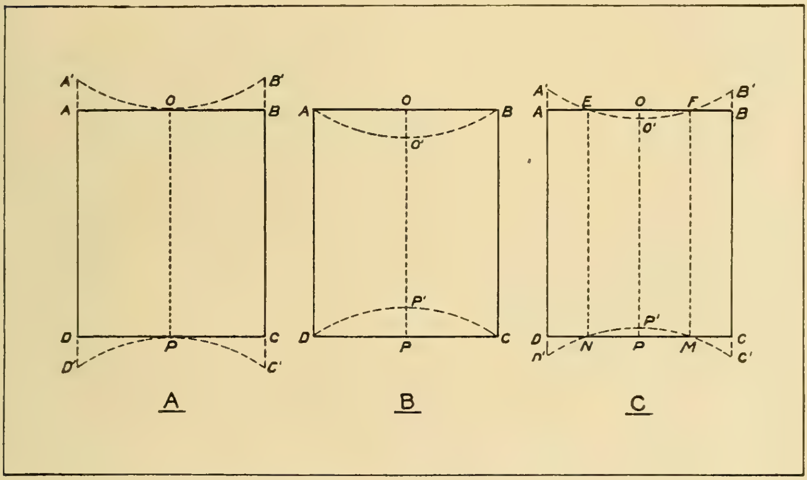

FIG. 8.—Illustrating changes in area due to torsional warping of a rectangular surface. In A the line *O–P* on the axis of torsion has remained constant in length resulting in a net increase in area from *ABCD* to *A'OB'C'PD'*. In B the lateral edges have remained constant in length and the result of warping is a decrease in area from *ABCD* to *AO'BCP'D*. In C the area has remained constant during warping resulting in elongation of the margins, shortening along the axis, and no change along the neutral lines *E–N* and *F–M*.

rubber sheet would result in tensional stresses along the free margins and compressional stresses along the center line with a neutral zone of neither compression nor tension on either side of the center. These three cases are illustrated in Figure 8. In each case the rectangular area represents the outline of an undeformed surface. The area with curved ends represents the surface

which has been deformed by warping and then flattened out for comparison with the original area.

Cross-bending stresses resulting from torsional warping.—We have so far considered only the stresses resulting from change in area, and now turn to a consideration of the stresses due to warping or cross-bending. In Figure 9 a warped surface is represented in isometric projection. In one set of diagonals the lines curve downward toward their centers forming a synclinal depression. In the other set of diagonals the lines curve upward toward their centers and form an anticlinal elevation.

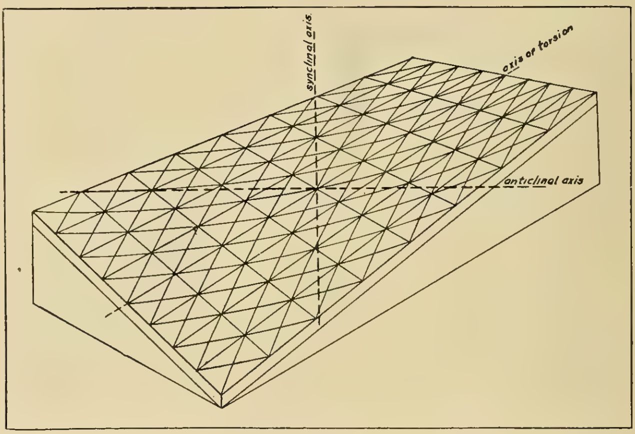

FIG. 9.—An isometric representation of a warped surface

If we consider a sheet of finite thickness to be thus deformed it is evident that on the upper surface compressional stresses will be developed at right angles to the axis of the synclinal depression and that tensional stresses will be developed at right angles to the axis of arching. At every point on the upper surface of this warped sheet there is a tensional stress and a compressional stress acting at right angles, each of them at an angle of 45° to the axis of torsion. On the lower surface it is evident that similar stress conditions exist but the tensional and compressional stresses are acting at angles of 90° to the similar stresses at the upper surface. These stresses are caused by cross-bending, and tensional conditions on one side mean compressional conditions on the opposite

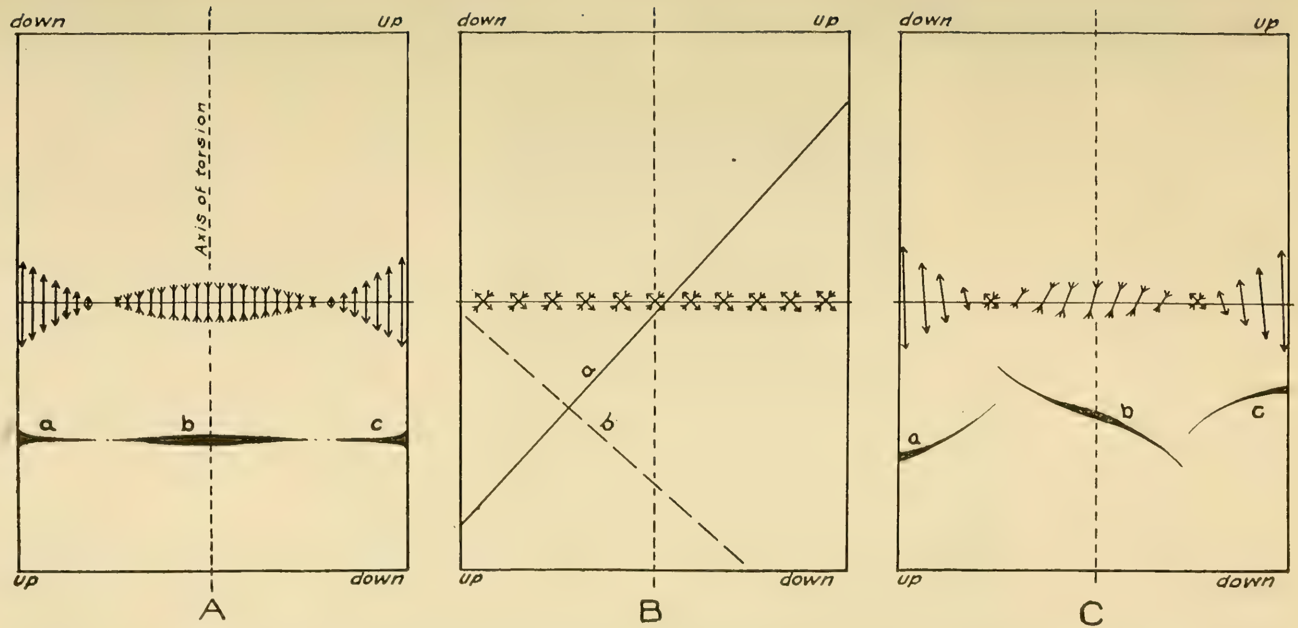

FIG. 10.—A. Stresses caused by local changes in area due to torsional warping, while the total area has remained constant. (See Fig. 8C.) Arrows indicate direction and relative magnitude of stresses *along any transverse line*. The heavy shaded lines indicate the direction and relative magnitude of resulting tension cracks at *a* and *c* and of compression fractures at *b*.

B. Stresses developed on the *upper surface* of a layer, due to bending caused by torsional warping. Arrows indicate direction and relative magnitude of stresses *along any transverse line*. The direction of tension cracks on the *upper surface* is indicated by the line *a*. The direction of tension cracks developed on the *lower surface* is indicated by the line *b*.

C. Resultants of stresses shown in A and B. Arrows indicate direction and relative magnitudes of resultant forces *along any transverse line*. The resulting type of tension cracks is shown by the shaded lines *a* and *c*. The shaded line *b* indicates the position and magnitude of the compression phenomena.

side just as in the case of a simple beam under load, in which compression is developed on the concave side and tension on the convex side.

Resolution of stresses due to change in area and to cross-bending—The stress condition at any point is the resultant of all of the stresses acting at that point. To determine conditions at a given point on the surface of a warped sheet it is necessary, therefore, to resolve the stresses due to cross-bending and the stresses due to areal change. In Figure 10A the stresses due to change of area caused by torsional warping are indicated in direction and relative

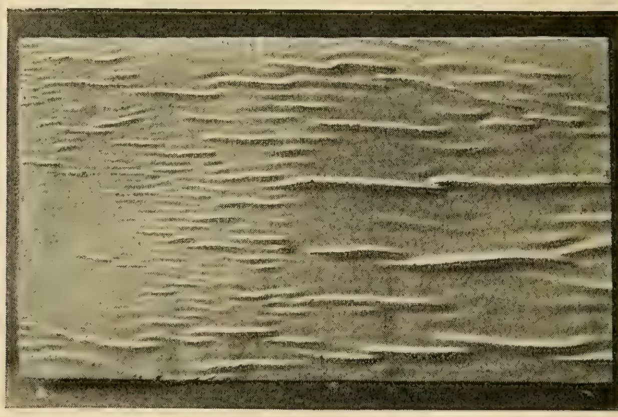

FIG. 11.—Plaster of Paris positive of folds produced by compression or shortening

magnitude by arrows. These represent the stresses occurring along *any transverse line of the warped sheet.* In Figure 10B the stresses due to cross-bending occurring along *any transverse line* of the warped sheet are shown by arrows in a similar fashion. In Figure 10C the resultants of the stresses in Figures 10A and 10B are shown. In Figure 10C typical cracks developed by tension and compression are shown at *a*, *b*, and *c*. The tension cracks *a* and *c* should begin at nearly 90° with the edge at the margin, and gradually curve to an angle of 45° at the neutral line. The curved line *b* indicates the strike of inclined thrust fractures which would be developed by compression. It is of interest to compare these curves with the tension cracks developed in paraffin on a rubber

sheet, illustrated in Figures 6 and 7. In this experiment constant distance between the clamps was maintained and compression along the center line thus prevented. The tension cracks are evidently due to a combination of cross-bending and stretching and are in accord with the conclusions indicated in Figure 10C.

Depending on the relative intensity of the stresses due to change in area and those due to cross-bending, the curvature of the cracks would vary from the position in Figure 10A, due only to change in area, to the position shown in Figure 10B, due only to cross-bending.

FIG. 12.—Vertical view of reproduction in plaster of Paris of folds produced by shearing deformation. The direction of movement is indicated by arrows and the amount of deformation is shown by the shape of the block.

Relative intensity of stresses due to cross-bending and those due to change in area.—With a given length of torsional axis the amount of cross-bending is a function of the angular displacement by torsion and is independent of the width of the warped sheet. The change in area (and therefore the tensional and compressional stresses), however, is a function of the width of the sheet as well as of the angle of torsion. It follows, therefore, that in narrow strips deformed by torsion, cross-bending stresses may be dominant while in wide areas a small angle of torsion with a small amount of resultant cross-bending may develop relatively large tensional and compressional stresses. Cross-bending stresses also increase with the thickness of the individual beds.

The classical experiment of Daubrée,[1] in which he twisted a narrow strip of glass and obtained systematic sets of fractures at approximately 45° with the axis of torsion, is familiar to most students of structural geology. The fractures thus developed in the glass are evidently due to cross-bending. The writer has repeated the Daubrée experiment and found that one set of fractures in the glass developed as tension-cross-bending cracks on one surface and that the other set of fractures at right angles to the first developed as tension-cross-bending fractures on the opposite surface. Therefore, a brittle rock formation broken in the manner illustrated by the Daubrée experiment would show a conspicuous set of tension cracks at 45° to the axis of warping and the other set would not be apparent, as it would be developed from the underside of the deformed rock stratum. In other words, if we look for a repetition of the Daubrée experiment in the field we should look for only one set of parallel tension cracks.

Use of the apparatus in the study of folds.—Previous experimentation in the reproduction of the structures of folded rocks in the laboratory has, so far as the writer is aware, been by means of the type of apparatus employed by Willis.[2] This type of apparatus with various modifications has been used by Hall, Lohest, Favre, Daubrée, Cadell, and others. In his investigation of the mechanics of Appalachian structure Willis used an apparatus of the piston or plunger type in which a series of wax layers of varying consistency were built up to resemble in their relative competence the rocks occurring in the Appalachian region. A load of shot was superposed to simulate the weight of overlying sediments and deformation was accomplished by forcing a piston or plunger against the end of the aggregate by means of a screw. Willis found that with flat-laying layers single folds were developed near the plunger and that repeated folds could be developed only when certain portions of the beds had an initial dip or when the first fold next to the plunger piled up material to such thickness and strength as to develop, as it were, an extension of the plunger which in turn caused a secondary fold in front of it.

[1] G. A. Daubrée, *Études Synthetiques de Gêologie Expêrimentale,* pp. 507–15.

[2] Bailey Willis, "Mechanics of Appalachian Structure, *Thirteenth Ann. Rept. U.S. Geol. Survey,* Part 2 (1893), pp. 241–53.

The apparatus of Willis permits deformation only by straight shortening or compression and does not afford means of studying the nature of folds developed by lateral shearing movements. It seems probable that the movements between great earth masses are in the nature of shears rather than simple straight-line compression. In other words, *the application of a compressive force directly toward the point of maximum resistance would be less probable than the development of a couple which would cause what has been called a rotational stress.*

It does not appear to the writer that rocks have been folded by forces transmitted to them in a manner at all similar to the action of a piston against a more or less confined mass but that shortening of the earth's crust has resulted from great compressive forces extending to some depth, and that the fracture and folded rocks within the zone of our observation have received from the rocks beneath, in a large measure, the force which deformed them. In other words, most of the faults or folds are the result of the riding or dragging of the upper layers by the underlying materials.

The writer has attempted to apply to the study of folds the methods used in the study of fractures already described. The two pieces of apparatus shown in Figures 1 and 4 were employed but instead of the thin brittle coat of paraffin a very thin layer of plastic wax (made by mixing beeswax and Venice turpentine) was applied and over this, while the wax was still sticky, a sheet of tinfoil was carefully spread. When the rubber sheet was allowed to shorten, or was deformed by shear, the layer of wax and tinfoil developed a series of folds. It was found that a very thin sheet of rubber served the same purpose as the tinfoil. The purpose of the thin sheet of rubber or tinfoil is to supply a layer with a certain small amount of competency. A layer of wax alone is entirely incompetent and follows the deformation of the rubber sheet without development of folds. A thin layer of tinfoil, sheet rubber, or waxed paper supplies the element of competency which results in the development of folds.

Folds developed by pure shortening or compression.—The apparatus shown in Figure 2 was employed, with a layer of plastic wax covered by a sheet of thin dental rubber. The shortening was

produced by allowing the thick rubber sheet to contract. This resulted in the development of the system of folds illustrated in Figure 11. This figure represents a positive reproduction of the surface of the specimen in plaster of Paris. The original specimen was not of a nature to be easily photographed. This experiment and others of the same type show a set of folds striking in a direction at right angles to the direction of shortening. All of these folds pitch at the ends and disappear. Depending on the thickness of the wax and the behavior of the rubber sheet, shortening is accomplished by a few large folds or by a larger number of smaller folds. An interesting overlapping of the folds is noted. Whenever a fold terminates by pitching, another fold appears overlapping it and continuing the necessary amount of shortening. The experiments demonstrate very well that pitching folds do not necessarily mean cross-folding but that they are developed in flat-lying beds with perfectly even application of shortening stresses.

Development of folds under conditions of shear or rotational stress.—The apparatus used is illustrated in Figure 4, except that in place of a thin layer of paraffin, a very thin layer of plastic wax was applied to the very tightly stretched rubber sheet and over this a sheet of tinfoil was carefully spread, care being taken to secure perfect adhesion of the tinfoil to the underlying wax. Deformation was accomplished by causing the slidable clamp to move parallel to the other clamp by means of the screw. This resulted in a set of folds in the tinfoil-covered wax layer, shown in Figure 12. The illustration is from a photograph of a positive reproduction of the specimen in plaster of Paris. The direction of shearing forces is shown by the arrows and the amount of deformation by the shape of the parallelogram which was originally rectangular. The folds, it will be noted, have their axes parallel to the direction of elongation of the mass. All of them are pitching folds. They illustrate the phenomenon of repeated folds. Like the previously described experiment they demonstrate that pitching folds do not necessarily mean cross-folding or shortening in the direction of the axes. As a matter of fact, in this experiment tensional stresses existed in the direction of the axes of the

folds and actual open ruptures in the tinfoil occurred across some of the folds but were not preserved in the process of casting.

A rather striking similarity between the folds illustrated in Figure 9 and the structure of the southern Appalachians is apparent and the writer ventures to suggest that perhaps certain of the characteristics of the southern Appalachian structure, such as repeated folds, pitching folds, and repeated thrust faults, may receive a certain amount of new light by viewing them with the conditions of the above-described experiment in mind. Whether the deformation was accomplished by straight compression between the oceanic segment and the continental mass or by a shearing movement between these great segments cannot be said. It seems, however, that the latter is rather more probable mechanically and that the foregoing experiment demonstrates that the folds of the Appalachians could have been produced by such shearing movement.

PRELIMINARY DESCRIPTION OF A NEW SUBORDER OF PHYTOSAURIAN REPTILES WITH A DESCRIPTION OF A NEW SPECIES OF *PHYTOSAURUS*

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The Triassic beds exposed in a narrow strip along the eastern edge of the Staked Plains in western Texas have not been intensively studied and are now grouped together under the name given by Drake, the Dockum beds. Drake recognized an indefinite tripartite division of the beds which may later be distinguished as recognizable horizons. The vertebrate remains which have so far been recovered from these exposures are all members of the reptilian order Parasuchia and of the stereospondylus stegocephalia and are indicative of an upper Triassic age. . Summary accounts of the reptilian forms previously described have been given by McGregor and Mehl.[1]

In the year 1917 the author, while on a hurried trip across the plains, found near the now little used crossing of the Blanco or Catfish River on the road from Spur, in Dickens County to Crosbytown, in Crosby County, a series of vertebrae, with portions of the dorsal armor, of a reptile which appeared to be of the usual phytosaurian type and were referred, in the museum catalogue, to *Phytosaurus buceros* Cope with question. In 1919 a chance was afforded to revisit the locality and considerably more of the same specimen was recovered. The material now in hand includes most of the vertebral column with exception of the posterior part of the tail, much of the dorsal armor and the skull, lacking the anterior end of the nose and the lower jaws. The skeleton was found in a sandy clay mixed with abundant fragments of vegetation and the bones were coated with a tough layer of gypsum which has in places penetrated and rotted the bones and in other places left

[1] J. H. McGregor, *Mem. Am. Mus. Nat. Hist.*, Vol. IX, Part XI, 1906; M. G. Mehl, *Jour. Geol.*, Vol. XXIII (1915), p. 129.

them in singularly good condition. The bones were disturbed when deposited so that only a few of the cervical and of the dorsal vertebrae were found in series. That the bones are those of a single individual is indicated by the fact that they were found in a single mass and that no other bones were found, even after a careful search, within a half-mile of the small patch where they were found, but that there is some room for doubt is indicated by

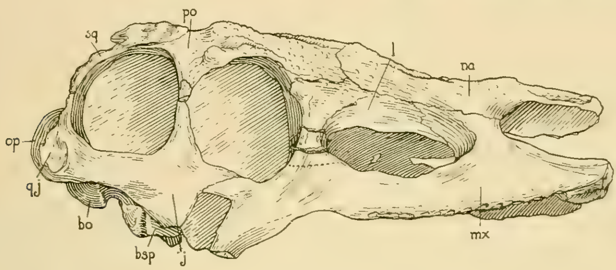

FIG. 1.—Lateral view of the skull of *Desmatosuchus spurensis*, $\times\frac{1}{4}$

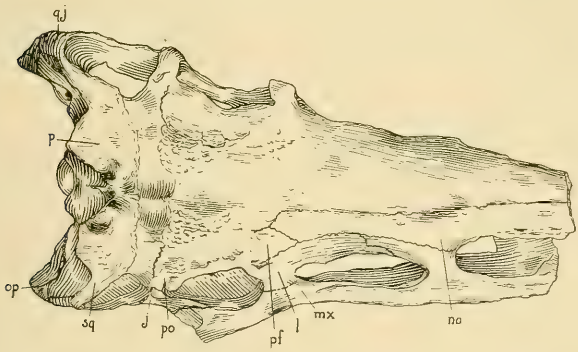

FIG. 2.—Upper view of the skull of *Desmatosuchus spurensis*, $\times\frac{1}{4}$

the fact that it seems impossible to fit two of the isolated cervicals into the series and that there are more dorsals than are usually found in the Parasuchia. These points are significant because the skull and the dorsal armor are so radically different from any form yet found while the vertebrae are typically Parasuchian. If, though it seems impossible at present, the remains are finally shown to belong to more than one individual, the skull must remain the type of the new sub-order and the vertebrae and dorsal armor must be described separately as a new form.

The character of the skull is shown in Figures 1, 2, and 3. It is astonishingly small for the size indicated by the vertebral column. The basi-cranial region is distinctly phytosaurian in size and the arrangement of the elements but the skull as a whole shows several marked peculiarities. There is a single large lateral temporal fenestra with no trace of an incipient or disappearing upper fenestra. The quadrate is so far reduced that it occupies a depression bounded by the opisthotic and the quadrato-jugal (?); the large, laterally directed orbits are preceded by large, elongate antorbital vacuities and these by smaller, elongate narial openings which lie entirely on the side of the nose; the teeth are small (as indicated by the sockets and a single poorly preserved tooth), are of equal size throughout the length of the maxillary, and were set in deep sockets; the posterior surface of the skull is completely closed except for the large foramen magnum and two small openings, amounting only to foramina, which occupy the position of the posterior temporal openings.

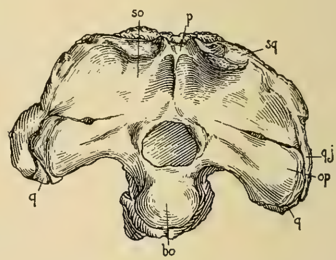

Fig. 3.—Posterior view of the skull of *Desmatosuchus spurensis*, $\times\frac{1}{4}$

The anterior end of the skull is missing but there is every indication that the nose was short. The close anchylosis of the bones and the coarse sculpture of the upper surface of the skull prevents the determination of many of the sutures; such as have been located are indicated upon the figures. As it has been shown by v. Huene and others that *Aëtosaurus* possessed upper temporal openings and as such openings are present in the Proterosuchia, their absence in the form here described is alone sufficient to indicate its isolated position.

The vertebral column so closely approaches that of the Parasuchia that it need not be discussed in a preliminary description.

The dorsal armor consists of four rows of plates, two on each side of the median line. The rows are made up of incomplete rings covering the dorsal portion of the body. Whether there was any armor on the sides or the abdomen is uncertain; a single

small plate of irregular form such as occurs on the lower part of the body of the Parasuchia was found with the specimen but its position is uncertain.

The dorsal armor is most conveniently described as a series of transverse arches. The first five are not metamerically arranged with relation to the vertebrae; they cover the first ten vertebrae, rather more than the whole cervical series; posterior to this the plates correspond in number and position with the vertebral segments below. Each arch consists of a pair of median plates with a low blunt spine or knob, and a pair of outer plates which carry spines of varying size and form. The plates of the first five arches have only a slight sculpture, those posterior to the fifth have an increasingly heavy sculpture of pits and ridges which soon becomes very coarse. The form of the various plates is shown in Figure 4, which is a semi-diagrammatic restoration of the dorsal armor. Except for the three posterior dorsal arches and the median caudals there is evidence for all the parts. The arrangement of the plates is such as is dictated by the form and characters of the units, none having been found in sequence posterior to the cervical region.

The first five arches show a gradual increase in the size of median plates and a rapid increase in the size of the spines upon the lateral plates. In the fourth arch the median and lateral plates of the right side are co-ossified and in the fifth arch the median plates of both sides and the lateral plate of the left side fit well together; in these arches there can be no doubt of the position and direction of the spines and by analogy with these the position of the other plates and spines is determinable. The fifth arch is most astonishing in the development of the relatively enormous spines which extend outward almost horizontally and curve forward over the third and fourth arches. In all of the arches of the cervical region the plates are thickened at the point of juncture in the same arch and thinned anteriorly and posteriorly to permit of the overlapping from before backward and allow for slight vertical movement of the head and neck; any lateral movement, as indicated by the form of the plates and the faces of the vertebral centra, must have been very slight.

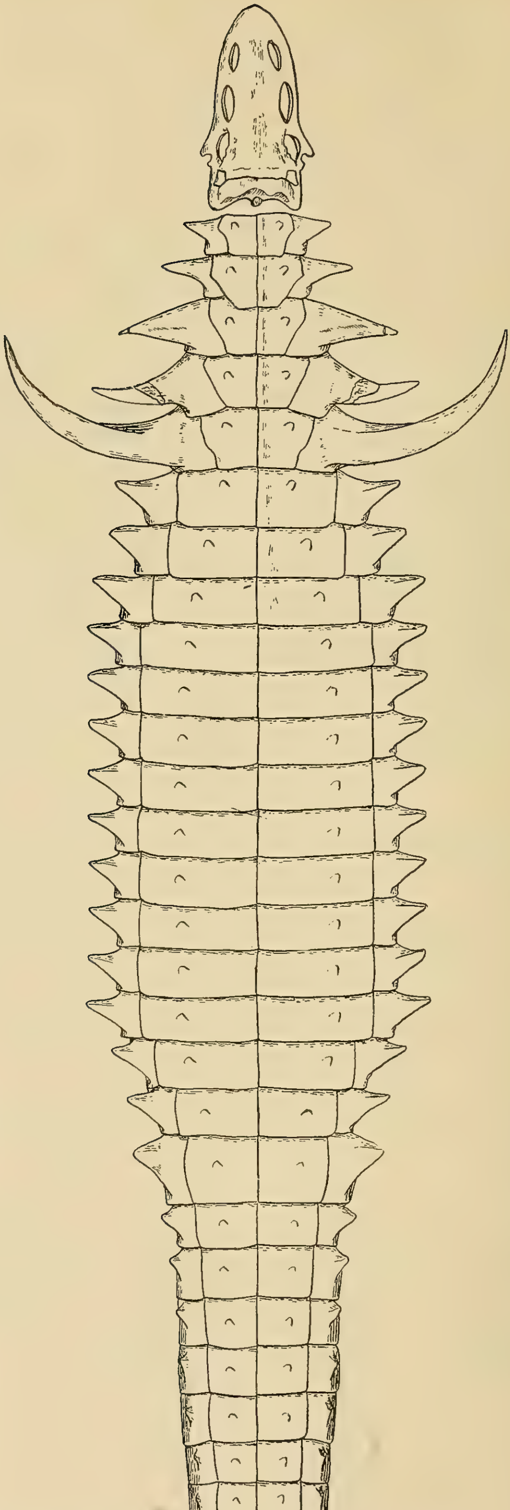

FIG. 4.—Restoration of the dorsal armor of *Desmatosuchus spurensis*, $\times\frac{1}{24}$

Posterior to the fifth arch the median plates become shorter antero-posteriorly and elongate laterally to accommodate the broadening of the back. The lateral plates have a distinctly angular form, the inner half of the base shorter and nearly horizontal, the outer half longer and extending outward and downward at a slight angle. The spines are directed outward and slightly forward. In the pelvic region is placed a broader arch followed by a narrower one; this arrangement is only tentative, but the plates can hardly go elsewhere and it has been pointed out to the author by Professor Alexander Ruthven that such an arrangement of scales and scutes is not uncommon in living forms. Only the anterior portion of the tail is represented and only by plates of the lateral series. It is altogether probable that the median plates gradually disappeared as in the living Crocodilia. The lateral plates have well-developed spines and the outer half of the base is elongated and extends downward almost directly in the same plane as the outer side of the spine, indicating that the sides of the tail were elevated and flattened, not rounded. The length of the tail is uncertain.

The exact position of this peculiar form is undeterminable as yet; its phytosaurian affinities are beyond question, but whether it is to be regarded as a highly specialized form of a more primitive type retaining characters of the primitive single-arched reptiles and placed near the origin of the Parasuchia, or a specialization of a more advanced type, remains to be determined after more complete preparation and the assemblage of the material in a mount. An attempt to obtain more material is in progress.

For this new form, indicating the skull as the characteristic portion of the holotype, I would suggest the name *Desmatosuchus spurensis*, with the family and sub-order *Desmatosuchidae* and *Desmatosuchia.*

ON A NEW SPECIES OF PHYTOSAUR FROM THE DOCKUM TRIASSIC BEDS OF TEXAS

While on a trip through a portion of the Triassic beds of Texas in the summer of 1919 the author was privileged to examine the collection of Mr. George D. Doughty, of Post City, Texas. In this

collection is the posterior portion of the skull of a large Phytosaur preserved in a soft yellow clay. The bones are somewhat rotted and broken but, as is common in specimens preserved in such a matrix, the sculpture and the sutures are exquisitely preserved. Mr. Doughty was so kind as to loan this specimen to the author for study and illustration. As preserved and collected, the posterior part of the top of the skull and the left side are present as far forward as the nares and the posterior end of the antorbital opening. The lower part of the skull is lost and the occipital region is represented by a detached fragment. The skull was distorted in fossilization so that the left temporal region is pushed outward at a decided angle. Figures 5 and 6 show the sculpture of the bones and the position of the sutures so clearly that extended description is unnecessary.

The lateral temporal opening is rhomboidal in outline with the long axis inclined obliquely forward and back. Its upper border is formed by the squamosal and postorbital. The squamosal is fairly flat on the upper surface and marked with a low relief of broad rugosities. The descending process on the outer side is smooth and widens toward its connection with the quadrato-jugal. The posterior end is widened and the inferior face is marked by two shallow, elongate, depressions, probably the location of cartilaginous attachment to the opisthotic. Just anterior to these there is a deep pit which received the head of the quadrate. There is a total lack of any descending, hooklike process posterior to the quadrate and defining the otic notch.

The parietals are flat or slightly concave; the posterior ends are broken off but there is clear evidence that the posterior ends were below the level of the squamosals and that there was no elevated arcade defining the posterior border of the upper temporal opening.

The quadrate was erect and its greatest breadth lay almost at right angles to the squamosal and the quadrato-jugal. Its anterior face is sharply concave, the inner border extends more forward than the outer and is very thin; apparently only the lower part of this inner edge united with the pterygoid.

The quadrato-jugal is peculiar in its mode of articulation with the jugal and the squamosal; the anterior and upper edges are

split and the lower edge of the squamosal and the posterior edge of the jugal are deeply dovetailed into the quadrato-jugal. This relation is clearly shown by the distinct and perfectly preserved sutures. From this peculiar relation it follows that the quadrato-jugal occupies very nearly as large an area on the inner side of the

FIG. 5.—Upper view of the skull of *Phytosaurus doughtyi*, $\times\frac{1}{4}$

temporal arch as on the outer, though it forms but a small portion of the posterior lower edge of the temporal opening. The attachment of the quadrato-jugal to the quadrate is by a broad, flat suture, interrupted by a good-sized quadrate foramen.

The jugal extends forward in a nearly straight line, not rising sharply or even bending upward to form a notch below the lateral temporal opening. It is not certain, but possible, that an anterior

extension of the jugal took part in the posterior edge of the antorbital opening. On the inner side of the anterior lower angle of the jugal are two articular faces which are separated by a deep groove; this when opposed to the maxillary would form a large foramen.

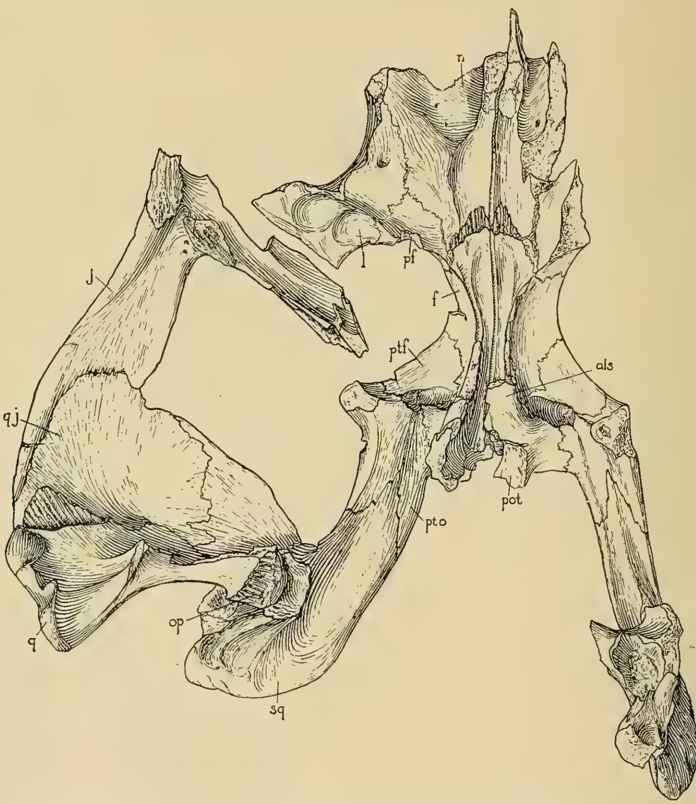

Fig. 6.—Lower view of the skull of *Phytosaurus doughtyi*, $\times\frac{1}{4}$

The orbits are nearly circular and are separated from the lateral temporal opening and the antorbital opening by strong bars. The anterior bar, formed by the lachrymal, is without sculpture but there is no indication of the opening extending backward in a depression on the surface of this bone.

The nasals are nearly flat in their posterior part but rise sharply to the posterior edge of the nares, which open upon a considerable

elevation. The nasals are short, not extending, apparently, anterior to the openings, and they do not separate the nares. The septum is formed by thin, paired plates which rise from below, as in most of the Phytosaurs; these are apparently the mesethmoids. The surface of the nasals, together with the surface of the frontals and parietals, are deeply sculptured. The nasal canals extend sharply backward as well as downward.

On the under side of the specimen the walls of the brain case are broken and lost from a line above the otic region. The bones which form the remnant of the brain case extend forward in sharp processes which lie in grooves on the lower surface of the frontals; these are probably the alisspenoids. The channel for the forward extension of the olfactory portion of the brain is well defined. At the point of junction of the postorbital, postfrontal, and parietal there are deep pits, transversely elongate, on either side. The function of these is obscure; they are perhaps connected with the orbitopineal process of the brain described by Cope in the cast of the brain cavity of *Phytosaurus buceros*.[1]

MEASUREMENTS	MM.
Posterior edge of nares to posterior end of squamosal	406.8
Top of squamosal to base of quadrate	233.6
Width across lower face of quadrate	83
Interorbital space, narrowest	62
Center of foramen magnum to end of opisthotic	124.7

A consideration of this brief description and the accompanying figures will show that this specimen differs at least specifically, from any yet described, and the name *Phytosaurus* (*Machaeroprosopus*) *doughtyi* is proposed for it in honor of the discoverer.

From the published figures of *Phytosaurus kapffi* given by v. Huene[2] this specimen differs notably. The quadrate fits into a pit on the lower side of the squamosal and is supported above by the opisthotic and below by the pterygoid; the latter is attached to the lower half of the quadrate and does not appear on the posterior lateral face of the quadrate as suggested in Huene's Figure 15.

[1] *American Naturalist*, Vol. XXII, p. 914.

[2] *Geol. u. Paleontolog. Abhdlg.*, N.F., Bd. X, 1891, Figs. 14–16.

The opisthotic and pterygoid join the quadrate by separate attachments in a manner quite different from that suggested by Huene, Figure 16. From this and all other described Phytosaurs it differs in the absence of a descending hook from the squamosal posterior to the quadrate, outlining the otic notch.

From *Paleorhinus*[1] it differs in the more posterior position of the nares, these lying over the antorbital opening as in the Phytosaurus type rather than anterior to it as in the Mystriosuchus type. The nasals are shorter and do not separate the nares nor extend anterior to them. No otic foramen is present. The quadrate foramen is entirely on the posterior face of the skull. The pre-frontal is much shorter and lies almost entirely anterior to the frontal. The lachrymal is stouter and forms a broad bar between the orbit and the antorbital opening. There is no evidence of a depression extending to the lachrymal from the posterior edge of the antorbital foramen and the lachrymal had little or no connection with the maxillary. The lower edge of the lateral temporal opening is convex upward, not concave.

From *Angistorhinus* it differs in the quadrangular rather than the oval form of the lateral temporal opening; in having the parietal-squamosal arcade depressed; in that the orbits are rounded instead of oval; in the position of the orbits which are more anterior in reference to the lateral temporal opening; in that the parietals meet anteriorly in a recess rather than in a point; and in that the opisthotic is more spatulate at the outer end.

From *Machaeroprosopus* it differs in the greater distance between the center of the orbit and the posterior end of the nares, 74 mm. instead of 40 mm. The nasals do not include nor extend in front of the nares. The frontals are longer and narrower; the jugals probably take little part in the posterior edge of the antorbital foramen. The quadrate foramen is small. The pterygoid is absent but it does not appear that there could have been any extension in the form of a wedge or hook between the quadrate and quadratojugal, as described and figured by Mehl.

[1] Bibliographies of the American Triassic Phytosaurs are given by McGregor, *Mem. Am. Mus. Nat. Hist.*, Vol. IX (1906), Part XI; and Mehl, *Jour. Geol.*, Vol. XXIII, No. 2, 1915.

From *Phytosaurus buceros* it differs in the more rounded and shorter posterior process of the squamosal. The lateral temporal opening is larger and more quadrangular in outline. The antorbital opening was more rounded at the posterior end. The jugal passes forward in a nearly straight line, not bending sharply upward, to form a notch in the lower border of the temporal opening.

Mehl in his account of the skull of *Machaeroprosopus*[1] has indicated his belief that the form described by him is congeneric with Cope's *Phytosaurus buceros;* but because he agreed with Jaekel that Cope's form is a distinct genus and because Jaekel's name, *Metarhinus*, is preoccupied, he suggested the new name *Machaeroprosopus*. It is far from certain that the European type of Phytosaurus does not occur in North America; Huene has rejected Jaekel's distinction between *Phytosaurus buceros* and the European forms, and to the author it seems very doubtful on present evidence that such a distinction is justified. For this reason he prefers to refer the new species to the genus *Phytosaurs* (*Machaeroprosopus ?*) with Cope's *buceros* and Mehl's *validus* and *gracilis*.

[1] *Quart. Bull. Univ. Oklahoma,* N.S., 103 (1916), p. 21.

THE HEART[1] MOUNTAIN OVERTHRUST, WYOMING[2]

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CONTENTS

ILLUSTRATIONS

SUMMARY OF RESULTS

The recognition in 1919 of blocks of Madison limestone (Mississippian) overlying beds of the Bridger epoch (middle Eocene) in the McCullock Peak region, 12 miles east of Cody, Wyoming, shows that the overthrust fault recognized by Dake (2) in 1916 is much more extensive than first suspected. Dake mapped the fault in a belt 30 miles long, within which the extent of overthrust was estimated at 16 miles. He also noted the existence of thrust faults along the east front of Beartooth plateau, where pre-Cambrian rocks overlie "Red Beds" (Chugwater formation) but did not assume continuity with the Heart Mountain overthrust. The residuals on McCullock Peak show that the extent of overthrust is at least 28 miles and indicate that the fault should be traceable

[1] This spelling approved by United States Geographic Board, 1909.

[2] Published by permission of the director, United States Geological Survey.

over the entire eastern edge of Absaroka Range, perhaps for 125 or 150 miles.

On the basis of exposures in the mountain region, Dake was able to conclude that the overthrust took place after the deposition of his Fort Union (?) (early Eocene) beds and before the outbursts of the "early basic breccias (Neocene or upper Miocene)" described by Hague. The McCullock Peak outliers show that the overthrust is probably post-Bridger (middle Eocene).

It may be recalled that Richards and Mansfield (15*a*) concluded that the Bannock overthrust in southeastern Idaho was developed before the deposition of Wasatch beds (lower Eocene). Similarly Veatch (16*a*) concluded that the Absaroka overthrust in southwestern Wyoming was developed after the deposition of the Almy and Fowkes beds (lower Wasatch) and before the deposition of the Knight formation (upper Wasatch, lower Eocene). On the north, Willis (17*a*) concluded from physiographic rather than stratigraphic evidence that the Lewis overthrust was developed in mid-Tertiary time, and was completed before the Miocene epoch. Although further work will undoubtedly determine more closely the periods at which these four overthrusts were developed, it appears highly probable at present that, although they lie in a belt scarcely 500 miles long, they did not take place simultaneously. The Lewis overthrust may have been nearly simultaneous with the Heart Mountain overthrust, however.

A brief reconnaissance by the writer in the region west of Cody studied by Dake confirmed his conclusion that the overthrust beds were deeply eroded before the outbursts of the early basic breccias of the Yellowstone Park region (upper Miocene). Evidence obtained by the writer previously between Owl Creek and Wood River, however, indicates that there was conformable deposition of the Bighorn Basin Wasatch and the overlying tuffs and breccias of that region, which are here tentatively correlated with the "early acid breccias" of the Absaroka Range (lower Eocene). It is concluded that the overthrust took place after the deposition of the "early acid breccias" and before the outbursts of "early basic breccias" and is, therefore, middle Eocene or early Oligocene in age.

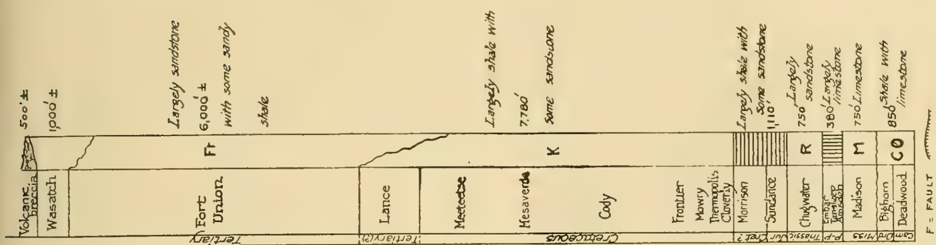
INTRODUCTION

It is the principal purpose of the present article to set forth observations in the McCullock Peak region that bear upon the extent and age of the Heart Mountain overthrust. It will be apparent, however, that such a profound structural feature must consistently fit into the complex Tertiary history of sedimentation and orogenic movements in the region, so that it seems advisable to set forth here some of the problems of the region and some of the data that must be adjusted to a correct and comprehensive interpretation of that history. As the writer has devoted parts of the field seasons of 1911, 1912, 1913, 1916, and 1919 to detailed investigations in three fifteen-minute quadrangles that lie between Cody and Thermopolis, southeast of the region in which the overthrust has been observed, some conclusions must be stated without giving much of the evidence on which they are based.

SURFACE FEATURES

The Bighorn Basin (4, 5, 14) is an elliptical area of low relief with few conspicuous hills or mountains, surrounded on the east, south, and west by mountain ranges. For purposes of physiographic, stratigraphic, and structural description, it may be considered as made up of two parts, a central part 75 miles long by 45 miles wide, which largely coincides with the area of Wasatch and younger beds, and a border belt 10 to 20 miles wide, which lies between the central part and the mountain ranges that surround the basin. These ranges include the Bighorn Mountains on the east, the Bridger and Owl Creek ranges on the south, and the Absaroka Range and Bear-tooth Plateau on the west. Figure 1 shows some of the features and geology of an area in the northwestern part of Bighorn Basin, which extend from the eastern edge of the Absaroka Range, across the border belt to the center of the basin. Figure 2 shows two sections across this region.

The central part of the basin contains large areas of flat uplands that lie several hundred feet above the nearby valleys. There are also extensive areas of bad lands where erosion has cut back into the uplands. The central part contains three conspicuous elevated areas that rise above the uplands, and that range from 1,200 to



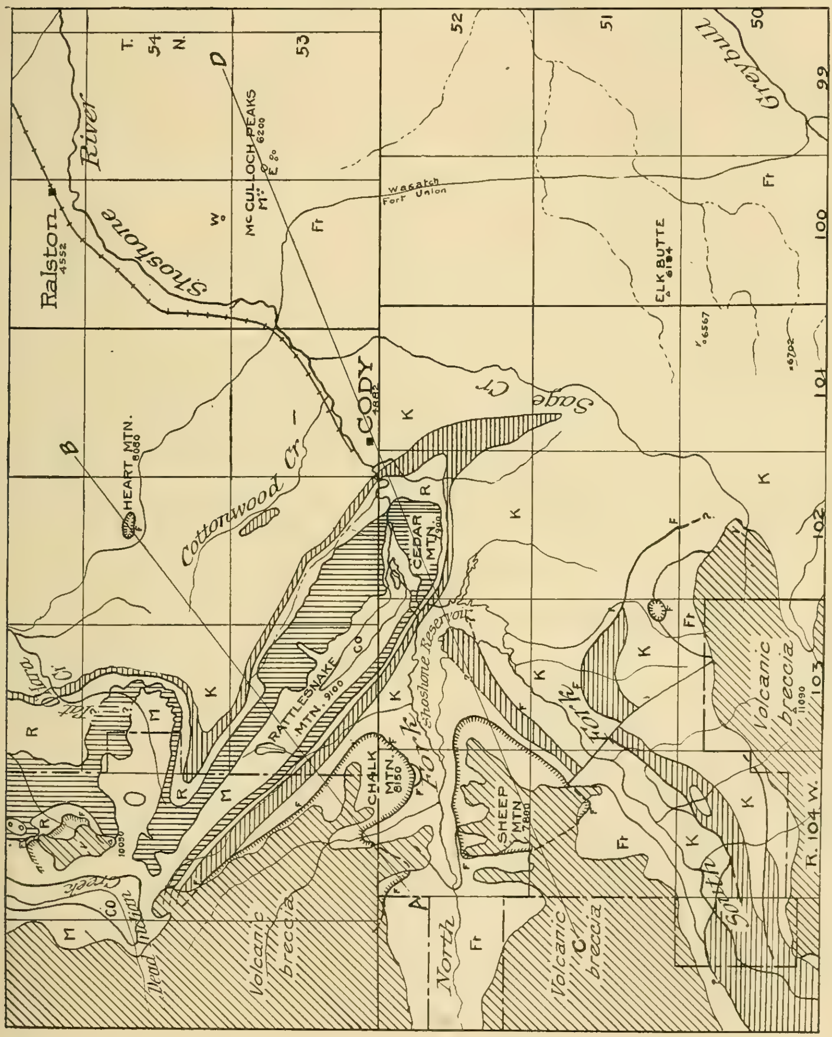


FIG. 1.—Sketch geologic map of region near Cody showing Heart Mountain overthrust. (Largely compiled from maps by C. L. Dake and C. A. Fisher.)

1,500 feet above the nearby streams; Squaw Buttes (6,200 feet), Tatman Mountain (5,800 feet), and McCullock Peaks,[1] three in number and approximately equal in elevation (6,200 feet). Heart Mountain (8,080 feet) is a conspicuous peak that lies west of the central part of the basin, where it merges with the border belt.

The border belt is largely made up of long stretches of flat upland terraces that rise gently toward the mountains. Most of the streams have cut broad terraced valleys below the uplands. The rocks exposed in this belt range from the Chugwater formation ("Red Beds") to the Fort Union formation (lower Eocene), and attain a maximum thickness of about 15,000 feet on the west side of the basin. The successive formations are brought to the surface in a series of pronounced folds whose axes are roughly parallel to a median trough in the central part of the basin. Dips that range from 15° to 60° are common along the flanks of the folds (14*a*).

In a broad way, the mountains that limit the basin on the east, southeast, and south, the Bighorn (4), Bridger (4), and Owl Creek (3) ranges respectively, are rather simple smooth ridges that coincide with extensive anticlines. The mountains west of the basin (10) are high and rugged and present an imposing front toward the basin. They coincide roughly with an area of volcanic tuffs, breccias, and flows that are a part of the extensive field of volcanic rocks which covers northwestern Wyoming and eastern Idaho.

STRATIGRAPHY

It will be sufficient at this place to state briefly the general features of the Paleozoic and Mesozoic sections and such details of the Fort Union, Wasatch, and younger rocks as bear upon the age of the overthrust and the physical conditions surrounding the process. The commonest underlying pre-Cambrian rock in this region is a rather homogeneous red granite which is locally cut by diabase dikes.

The Paleozoic and Mesozoic sections are separable into three groups on the basis of lithology and degree of induration, which measure their strength. The first and strongest group includes the Paleozoic limestones and associated sandstones and quartzites,

[1] Commonly referred to as McCullock Peak.

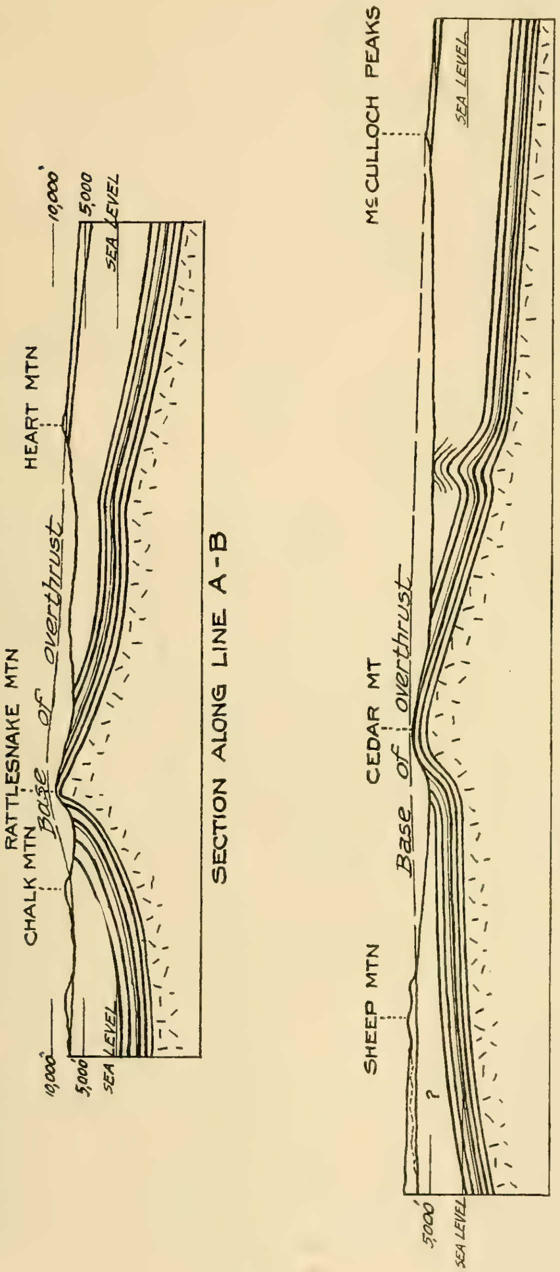


FIG. 2.—Cross-sections of the Heart Mountain overthrust

that include the beds from the Bighorn limestone (Ordovician) to the Embar group (Permian and Pennsylvanian), the sum of whose average thicknesses in this region is about 1,280 feet. Most of this thickness is beds of dense homogeneous gray limestone that range from 5 to 50 feet thick. This group is to be regarded as the most competent unit in the entire section.

The second group includes several distinct sandstone formations, such as the Chugwater (Triassic) about 750 feet thick, and Mesaverde formation (Upper Cretaceous), which is largely sandstone and about 1,200 feet thick. Both of these formations include some shale. As the Chugwater formation overlies the Paleozoic limestones and sandstones, it would tend to increase the strength of those beds.

The third and weakest group includes the remaining formations. The Deadwood formation (Cambrian) made up of shale and sandstone is 700 feet thick. The Mesozoic and Tertiary formations (12, 14) that are made up of thin soft sandstones, locally conglomerate, sandy shale, and shale include the Sundance, Morrison, Cloverly, Thermopolis, Mowry, Frontier, Cody, Meeteetse, Lance, Fort Union, and Wasatch formations, 13,600± feet thick.

It will be noted that the most competent unit is that which includes beds that range from the Bighorn limestone (Ordovician) to the Chugwater sandstones (Triassic) about 2,030 feet thick. If this section be compared with others of regions in which large overthrust faults have occurred, the thinness of the competent part of the section is impressive.

The characteristics and structural relations of those beds only that may bear upon the period of overthrusting will be presented here. The recognition of the Fort Union formation on the west side of Bighorn Basin is based upon numerous collections of leaves that have been studied and identified by F. H. Knowlton. The base is considered to be a conglomeratic sandstone, which is locally unconformable on underlying beds that range from the middle part of the Meeteetse formation (roughly equivalent to the Judith River formation of the Montana group) to the top of the Lance formation ("Ceratops beds"). This unconformity has only been recognized in one locality east of Oregon Basin for a distance of

15 miles where a maximum of about 2,000 feet of beds were here eroded before the deposition of the lowest Fort Union beds. The contact of these beds with the underlying Lance formation in a belt 50 miles southeast, however, yields no evidence of unconformity. The unconformity indicates local warping and erosion of the Lance and older beds before the deposition of the lowest Fort Union sandstone.

The top of the Fort Union formation in this region is a persistent unconformity at the base of beds that yield a large mammalian fauna until recently called Wasatch but now known to be characteristic of the Wind River formation (8, 9).

The unconformity is readily recognizable at every locality where dip cross-sections of the beds may be seen, but in strike sections it can only be detected by close study of the lithological features.

Within these limits, the Fort Union formation attains a maximum thickness of more than 5,250 feet and is made up of many beds of pale yellowish buff and white sandstone alternating with gray, olive, and red shale. The sandstones of the lower 200 feet commonly contain lenses of pebbles of many rock types. Black and gray chert predominate but red and gray quartzite, pale pink porphyry, gray sandstone, and silicified wood are common. Pink granite and coal pebbles are sparingly present but limestone has never been found. The chert pebbles have yielded an interesting collection of invertebrate fossils which are characteristic of the Madison and Embar formations. At least three coal beds occur in the lower 600 feet of the formation on the west side of the basin. Thus far, in this region, the formation has yielded a single vertebrate bone, but no invertebrate fossils. No bentonite or volcanic ash have been recognized in it.

There are good reasons for believing that the beds here considered as the Fort Union formation are part of an extensive sheet of sediments spread over a large area of Wyoming and Montana, at least as far west as the Rocky Mountains, and eastward into the Dakotas. They probably covered the site of the present Bighorn, Bridger, and Owl Creek Ranges. These beds are so involved in the folds of the border belt of the basin that it is concluded that these

as well as the long anticlines which coincide with the Bighorn, Bridger, and Owl Creek ranges, were developed after the beds were laid down. The folds are broken by many normal faults of small displacement, none of which appear to pass into the overlying Wasatch beds.

The term Bighorn Basin Wasatch has long been considered to include the sandstones and alternating olive and red clays of the central part of the Bighorn Basin, where they attain a maximum thickness of about 2,500 feet. These beds include light brown and white sandstones, gritty arkose and pale olive, gray, and red clays. The sandstones locally contain pebble zones of re-worked Fort Union materials, with the addition of limestone and granite which are absent or uncommon in those beds. Although bentonite has been reported east of Meeteetse (5), no unaltered volcanic tuff has yet been recognized. The beds are nearly horizontal over large areas in the center of the basin, and although the range along the border is commonly 3° to 10°, dips as high as 20° are known (9).

The beds of the central part yield a large vertebrate fauna which has been studied from time to time. Only a few invertebrate fossils are known in the beds (5). The recent careful faunal studies of Granger and Sinclair show that the Bighorn Basin Wasatch contains beds that range from "Paleocene" (their Clarks Fork beds) to uppermost lower Eocene (their Lysite or Upper Wind River beds) (7, 8, 9).

The early work of Eldridge (6) as well as the later work of Fisher (5) showed the presence of a persistent nearly horizontal layer, composed of sandstone and gray and red shale underlying volcanic tuffs in the region between Meeteetse Creek and Owl Creek in the southwest part of Bighorn Basin, and they were considered to be Wasatch. These beds outcrop along the south edge of the Meeteetse quadrangle and the west edge of the Grass Creek quadrangle which have been studied by the writer. In addition to the alternating olive and red shale and sandstones with local chert and quartzite pebble lenses, which are characteristic of the Wasatch deposits of the central part of the basin, there are thin beds of dark carbonaceous shale, carbonized plant remains, and

thin lenses of coal. The thickness of the layer ranges from 125 to 250 feet. It lies on a surface of low relief cut across the folded Cretaceous rocks, and as the base rises from an elevation of 6,000 feet near Owl Creek to 7,200 feet near Wood River, a distance of 21 miles, it appears to have been slightly warped since deposition. North of Cottonwood Creek a narrow east-west strip has been down-faulted about 360 feet.

Throughout this region, these beds are apparently conformably overlain by paper-thin carbonaceous shales that weather white, and these, in turn, by pale greenish volcanic ash and light brown tuff, locally indurated. About 100 feet above the typical Wasatch sediments, the well-stratified fine material is succeeded by coarser, cross-bedded light brown tuff and still higher by heterogeneous fine and coarse brown andesitic breccia that makes up the masses 3,000 to 4,000 feet thick in the region east of the Washakie Needles. Except for the reference to lava flows, which are not known between Wood River and Owl Creek, the following statement by Blackwelder might be considered an accurate description of conditions in the southwest part of Bighorn Basin (1*a*):

> At the northwest end of the Wind River Range, where it articulates with the mountains of Yellowstone Park, thick beds of volcanic ash and agglomerate with interbedded glassy lava flows rest upon the pre-Tertiary folded rocks, but are themselves younger than the Wind River Eocene. Traced eastward to Horse Creek, the Washakee Needles, and the valley of Owl Creek, this thick volcanic series is found to rest conformably upon the striped clays of the Wind River formation, with which they intergrade through gray, plant-bearing shales and greenish volcanic sandstones containing petrified logs. A closer examination of the volcanic beds shows that some of them are massive agglomerates, devoid of stratification, whereas other beds are distinctly stratified, cross-bedded, and occasionally interrupted by lenticular sheets of coarse gravel, suggestive of stream channels. The conditions indicated are those which would be found upon low gradient river plains adjacent to active volcanoes.

The stratified tuffs have yielded several collections of leaves, one collected by Mr. N. H. Darton (3*a*) on the Middle Fork of Owl Creek and one by the writer south of Sunshine. Both are considered characteristic Fort Union material by F. H. Knowlton. No vertebrate or invertebrate fossils have yet been found in the supposed Wasatch beds, or the overlying tuffs or breccias.

The relations between the beds described above, which may be referred to as the border Wasatch, to the Bighorn Basin Wasatch might be uncertain if it were not for the existence of remnants on hilltops in several parts of the border belt. These remnants have the same lithologic features as the border Wasatch and some of the beds rather high in the section of the Bighorn Basin Wasatch in the Tatman Mountain section. A longitudinal section through three of these remnants from a point south of Sunshine northeast toward the basin shows that they are part of a river channel which extended from the foothills of the border belt out into the basin with a gradient of 25 to 70 feet to the mile. It is the writer's opinion that the border Wasatch was laid down at the same time as some of the beds that make up the Lost Cabin or Tatman Mountain beds (upper Wind River) of Sinclair and Granger in the central part of Bighorn Basin. The particular significance of the border Wasatch beds is that they indicate that there has been little if any local folding of the Cretaceous and Fort Union beds of the border belt since upper Wind River beds were laid down. The border Wasatch has, however, been broadly warped and locally faulted.

Only tentative conclusions concerning the age and correlation of the stratified tuffs and breccias that overlie the border Wasatch can be made at this time. In considering this problem the writer has had the benefit of informal discussion with Dr. J. P. Iddings, who examined a large part of the area of the Yellowstone Park (11) and that covered by the Absaroka folio (10).

It may be recalled that along the headwaters of Lamar River (Cache Creek) and Clark's Fork (Republic Creek) several varieties of light colored andesitic tuffs and breccias, locally distinctly stratified, underlie the darker, basaltic breccias that cover a large area east of Yellowstone River and Lake, and north of the latitude of Greybull River (10). Although locally, the lower group ("early acid breccias") appears to merge upward with the upper group ("early basic breccias"), elsewhere there is evidence of considerable erosion of the lower group before the deposition of the upper group. The lower group yielded a large flora, considered by F. H. Knowlton to be Fort Union (lower Eocene), whereas the flora of the upper group, likewise large, is considered to be upper Miocene. From

the evidence of this region, one must conclude either (1) that the period of erosion intervening between the deposition of the two groups of breccias was brief and therefore that the floras are misleading, or (2) that the intervening period of erosion was rather long, probably persisting from upper Eocene time through Oligocene and lower Miocene time, as the floras indicate. Dr. Iddings agrees with the writer that the latter conclusion is more acceptable at present. He further considers that the lithology and flora of the tuffs and breccias between Owl Creek and Wind River warrant the tentative correlation of them with the "early acid breccias" of the Yellowstone Park region. It is apparent, however, that considerable additional work must be done before the relations of the volcanic rocks of the southern Absaroka Range are proved.

MCCULLOCK PEAK EXPOSURES

The foregoing statement of the lithologic features and structure of the Fort Union and Wasatch beds of the Basin permit a more careful consideration of the exposures near McCullock Peak and the relations of the overthrust recognized by Dake west of Cody.

In previous descriptions of this region, the name "McCullock Peak" has been applied to the central part of a high rugged area, about 4 miles long by 2 miles wide, 12 miles east of Cody. (Figure 3 shows a view of the McCullock Peak area from the west.) In the following description of the region, three culminating summits will be referred to as West Peak, Middle Peak, and East Peak, respectively. Although extensive gravel-covered terraces extend south from the peaks for several miles, the entire elevated region is completely surrounded by typical bad lands, and the rock exposures are uncommonly good.

West Peak lies about two miles northwest of Middle Peak and is connected with it by a sinuous rugged ridge. It is the culminating point of a rugged bad lands area carved from nearly horizontal Wasatch beds. It is almost devoid of vegetation and the terraced ridges of alternating gray, olive, and red shale and sandstone present an impressive picture from the east, north, and west. It was not visited by the writer, but several attempts to ascend it by horseback from the west are known to have failed.

Middle Peak may be readily ascended from the south along a gravel-covered terrace of gentle gradient. The summit is smooth and the adjacent slopes, except on the north and west, are covered with grass and dwarfed sage-brush. If viewed from the west, the summit appears to be a part of the terrace which extends southward, but if critically viewed from the south it appears to be a smooth hill that projects about 200 feet above the extension of

FIG. 3.—The McCullock Peak region viewed from the southwest, near Cody, Wyoming. West Peak lies on the left; East Peak rises above the terrace on the right; Middle Peak is the low cone just left of East Peak.

the terrace. In other words, it appears to be the residual mass of a more imposing hill that was in existence while the plain of which the terrace is a remnant was being formed. Good rock outcrops are confined to the west, north, and northeast slopes of Middle Peak, where nearly horizontal sandstones, locally arkosic, alternate with pale olive and red clays. The material is similar to that which makes up the bulk of the Bighorn Basin Wasatch. The

fossils which are described below were collected from a 50-foot zone of gray, olive, and red clays that are well exposed along a narrow ridge 1,000 feet northeast and 150 feet stratigraphically below the summit.

The fossils were first referred to J. W. Gidley of the United States National Museum, but, as field parties from the American Museum of Natural History have closely studied and made numerous collections from these beds, it seemed advisable to refer the fossils to them also. The statements of Mr. Gidley (*a*) and of Mr. Walter Granger (*b*) are attached:

a) A preliminary report was furnished to Dr. Stanton on November 25 (unofficially). It was as follows:

"No. 1. The largest tooth is a right upper third or last molar of *Helaletes;* cf. *nanus* Marsh. Not known outside the Bridger horizon.

"No. 2. The next smaller tooth is a last left upper molar of *Eohippus* sp.

"No. 3. The fragment of jaw containing two teeth I have not been able to definitely determine."

In addition, I may now say that a further study of the small jaw fragment seems to warrant referring it to *Hemiscodon pucillus* Marsh, with which it agrees almost exactly in size. This determination, however, cannot be made positive without comparing it with the type, which is probably in the Yale Museum collection. This is a Bridger species.

It would thus seem that the three specimens represent a Bridger fauna, although the Eohippus tooth suggests Wasatch rather than Bridger affinities.

b) I have examined the three specimens of mammal teeth from Eocene beds near the top of McCullock Peak, Wyoming, and submit the following determinations:

(1) *Helaletes*, a last upper molar of the right side.

(2) *Eohippus*, a last upper molar of the left side.

(3) *Tetonius* or *Absarokius*, a fragment of the right mandible, containing the first and second molars.

The Lophiodont genus *Helaletes* has hitherto been recorded only from the Bridger, but it might reasonably be expected from the uppermost levels of the Lower Eocene since another Bridger perissodactyl, *Hyrachyus*, has recently been found in the upper horizon of the Wind River (Lost Cabin beds).

The Hyracothere tooth shows characters most closely approached by the smaller specimens of *Eohippus* from the upper Wind River, as well as by specimens from the upper Huerfano, which is now regarded as the probable equivalent of the almost barren Bridger A.

The tiny jaw fragment of the Tarsiid cannot definitely be assigned to either of the genera mentioned because it lacks the diagnostic front teeth.

Tetonius, the type species of which is *Anaptomorphus homunculus* Cope, is recorded from the Gray Bull and Lysite horizons of the Bighorn and Wind River basins respectively, while the closely related *Absarokius* is from the Lysite and Lost Cabin horizons of the Wind River. The jaw appears to be of a new species, somewhat more progressive than any described form of either genus.

These three specimens seem to represent a fauna intermediate between that of the upper Wind River and that of Bridger B. It may belong to the base of the Bridger (Hor. A), the mammalian fauna of which is practically unknown, correlation with the upper Huerfano being made on a single specimen of Titanothere. In any event the McCullock Peak horizon is close to the border line between the Lower and Middle Eocene.

Dr. W. D. Matthew, who has also examined these teeth, concurs in the above identifications and in the conclusions regarding the age of the beds in which they were found.

Blocks, bowlders, and smaller fragments of dense cream to buff limestone are found on the summit of Middle Peak, as well as on the ridge that extends south and in the ravines cut below it. In an area on the summit about 600 feet square, there are no less than twenty blocks more than 3 feet in maximum dimension, and the largest is $5 \times 5 \times 10$ feet. Most of the blocks are rudely rectangular and appear to be bounded by bedding planes and joints, although the surfaces are pitted and grooved by the solvent action of water. The blocks are irregularly distributed and there can be no doubt that they are not in place. The size, shape, and composition of the blocks as well as their distribution, are similar to those described by Granger and Sinclair (9*a*), to which a glacial origin was ascribed. Fossils collected from one of the blocks have been examined by Dr. George H. Girty, who reports that the following species are present: *Cliothyridina, crassicardinalis, Eumetria Verneuliana, Schuchertella aff. Chemungenis, Spirifer centronatus, Triplophyllum* sp. Dr. Girty states that this is a characteristic Madison fauna (Mississippian).

This collection may be compared with the following collection, also identified by Dr. Girty as belonging in the Madison limetone. It was obtained about 50 feet above the southwest base of the block of limestone that forms Chalk Mountain, west of Cody, where it overlies beds of Cretaceous age: *Triplophyllum excavatum, Schuchertella aff. Chemungensis, Camarotoechia metallica* (?),

Spiriferina soliderostris, *Cliothyridina crassicardinalis*, *Eumetria Verneuliana*, *Platyceras* sp.

South Peak lies about 8,000 feet southeast of Middle Peak and is formed by the conjunction of three smooth ridges that extend northwest, southwest, and east, respectively. The space between these two peaks is a smooth, rolling flat covered with sagebrush, and no rock outcrops were recognized in it. Just below the summit of this peak and well distributed around it there are six rugged outcrops of cream-colored limestone, each from 50 to 75 feet long. The limestone outcrops do not exhibit bedding but are highly shattered and several are entirely made up of angular fragments of limestone, one to ten inches in diameter, which are imbedded in a fine sand of similar material. The only fossils noted in these outcrops are a few crinoid stems, but the texture resembles that of the Madison limestone blocks on Middle Peak.

The best evidence of the character of the beds under the limestone is obtained at the head of a ravine on the northeast side of the peak, where the smooth surface near the summit merges with bad lands that show horizontal Wasatch material. No fossils were found at this locality. The evidence at South Peak indicates that a triangular cap of crushed Madison limestone, about 600 feet long and 400 feet across the base and about 80 feet thick, overlies horizontal Wasatch beds.

The summit of South Peak lies at the northwest end of an area about 3,000 feet in diameter within which there are eleven smaller and lower hills each of which shows outcrops of limestone breccia more than 50 feet long. Figure 4 shows one of the largest of these outcrops, in which the bedding is still preserved. It is 200 feet long, about 25 feet thick and, although it yielded no fossils, the texture indicates that it is probably part of the Bighorn limestone (Ordovician). Farther southeast these low hills merge with gravel-covered flat terraces that extend to the east and southeast toward the center of Bighorn Basin. Near the center of the hills, capped by limestone, there is a flat depression 500 feet in diameter at the northwest edge of which is Markham Spring, at an elevation of 5,850 feet. Even at the end of August, in the dry season of 1919, it yielded about two gallons a minute of clear non-alkaline water.

Another similar spring lies about 3,000 feet southwest at a lower elevation. These springs appear to be supplied from a thin mantle of mingled limestone breccia and sand from the Wasatch beds that becomes sufficiently saturated with water during the wet season to yield a small flow throughout the year. No other perennial springs are known within ten miles.

FIG. 4.—Bighorn limestone (?) overlying Wasatch (or Bridger?) beds on a hill near East Peak, McCullock Peak region, near Cody, Wyoming.

The significance of the McCullock Peak exposures may be briefly summarized. Before Dake's work was done in 1916, the McCullock Peak exposures might have been as puzzling as Heart Mountain to the geologists who examined that region some years ago (5, 6), and who considered that the block of Madison limestone which forms its summit was a plug bounded by a circular fault. In the light of Dake's work, there can be little doubt that the blocks of limestone in the vicinity of South Peak are parts of a layer of limestone that was thrust from the west, probably from the region

near Sheep Mountain between the north and south forks of Shoshone River, 28 miles west. It is impossible to imagine that the McCullock Peaks blocks are somehow related to another overthrust or to some obscure and complex structure, for the structure of the beds between the peaks and Sheep Mountain is completely shown in the canyon of Shoshone River (14).

The recognition of mammalian fossils characteristic of the Bridger formation of western Wyoming under the blocks of Madison limestone shows conclusively that the period of overthrust was no older than these beds.

PHYSICAL FEATURES OF THE OVERTHRUST

Sufficient information is not yet available to make a comprehensive statement concerning those features of the overthrust that are needed to interpret the conditions under which it developed. It may be that the thick masses of "early basic breccias" cover so much of the mountainward portion that a satisfactory explanation can never be given. The known exposures permit the following summary of its features:

1. The lithology of the beds and few fossils collected in the mountainward area indicate that the base of the overthrust is uniformly the base of the Madison limestone. Dake states that the base of the Heart Mountain block is Madison limestone. On the other hand, although the few bowlders on Middle Peak yield Madison fossils, the lithologic features of the East Peak remnants resemble the Bighorn limestone. The base of the overthrust is, therefore, probably not the same horizon throughout. A limestone breccia is present at the base of all of the blocks that were examined. In the few days available in the mountain region, the writer was unable to confirm Dake's conclusion that there are two surfaces of overthrust. Although the presence of Sundance fossils under the Chalk Mountain Block appears to be evidence that such is ithe case, the exposures along South Fork, where a lower surface s also mapped, do not appear to demand this interpretation.

2. The elevation of the base of the remnants of the overthrust block decreases from about 7,200 feet on Carter Mountain to, about 6,800 feet on Sheep Mountain, then increases to about

9,500 feet on the divide between Rattlesnake and Dead Indian Creeks. The base of the Heart Mountain remnant stands at about 7,200 feet and the McCullock Peak remnants from 6,100 to 6,200 feet. Rattlesnake Mountain, a persistent ridge which attains an elevation of 9,100 feet and lies between these two groups of remnants, was examined but does not appear to retain any remnants of the overthrust block, although it once overlay the mountain. It cannot be stated assuredly yet whether the differences in elevation here indicated represent the form of the original surface of overthrust or whether the surface has been subsequently warped. Although parts of the region have been warped since the deposition of the bedded tuff near Owl Creek, tentatively correlated with the "early acid breccias" (lower Eocene), the writer believes that a large part of the noted differences represent the form of the surface over which the block was thrust.

3. The structure and attitude of the remnants of the overthrust block indicate that it was a relatively simple, unfolded layer of rock. The thickness can only be conjectured. The entire Paleozoic, Mesozoic, and Fort Union sections above the Deadwood shale (Cambrian) are about 17,000 feet thick. In attempting to estimate the probable thickness of the block, it must be borne in mind that it was largely removed by erosion before the outburst of "early basic breccias" (upper Miocene). The writer would tentatively estimate the thickness near the mountains at 15,000 feet, but the eastern edge was probably much thinner.

4. The surface upon which the overthrust moved is cut across a sharply folded belt of rocks that range from the pre-Cambrian granite to beds that appear to represent horizon A of the Bridger formation. No part of this surface that has been studied appears to be a fracture across the beds, but it is probably a surface of erosion. To this extent it resembles Willis' interpretation of the Lewis overthrust (17).

5. Dake mapped the overthrust in an area thirty miles long and the McCullock Peak exposures indicate a minimum thrust of twenty-eight miles. Only casual consideration of the regional geology is needed to convince one that the overthrust must have involved a much larger area, over which it can probably be traced.

6. The relations of the border Wasatch and the residuals east of Sunshine indicate that the border belt of folds had assumed their present form and were truncated by erosion before these beds were laid down. Apparently, therefore, the folds were developed considerably earlier than the overthrust.

AGE OF THE OVERTHRUST

As a result of his work Dake concluded that the overthrust was younger than certain beds along the north and south fork of Shoshone River, tentatively correlated with his Fort Union (?) formation. He also concluded that the overthrust was older than the "early basic breccias."

The short time available to the writer in this region in 1919 only permitted the following conclusions:

1. The beds exposed along the north fork of Shoshone River under the "early basic breccias" (13), and locally under remnants of the overthrust block resemble lithologically those 1,000 to 1,500 feet above the base of the Fort Union formation in the Bighorn Basin and lack the arkoses which are rather characteristic of the Bighorn Basin Wasatch. On the other hand they yield collections of leaves, among which F. H. Knowlton has recognized "Aralia notata Lesq." which though considered to be a Fort Union species, has not yet been recognized in the Bighorn Basin Fort Union, but is present in most of the collections from the "early acid breccias" in Yellowstone Park and the tuffs north of Owl Creek. The beds yield numerous bone fragments, largely turtle skutes, not yet recognized in the Bighorn Basin Fort Union, but common in the Bighorn Basin Wasatch. Although existing evidence is conflicting, the writer is inclined to consider that the beds are to be correlated with the border Wasatch.

2. The overthrust is older than the "early basic breccias" because the breccias locally lie in channels cut 200 to 300 feet below the overthrust surface.

3. The period of erosion that followed the overthrust and preceded the deposition of the "early basic breccias" was sufficiently long to destroy most of the beds that made up the thrust block, for the thickest remnant, that which makes up the summit of

Sheep Mountain, is only 1,000 feet thick and there are large areas over which the block is completely removed and "early basic breccias" rest on Wasatch beds (?).

TERTIARY DEFORMATION AND SEDIMENTATION IN THE BIGHORN BASIN

The table opposite p. 556 is presented at this time in the hope that it may aid in a better understanding of the relation of the Heart Mountain overthrust to the other deformations of the Bighorn Basin. It is not considered necessary to present in this paper any more of the evidence on which the conclusions are based.

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PRELIMINARY CORRELATION OF TERTIARY DEFORMATION AND SEDIMENTATION IN BIGHORN BASIN

Geologic Age		Absaroka-Owl Creek Mountain Front		Bighorn Basin			
				Border Belt		Central Part	
		Deposition or Erosion	Deformation	Deposition or Erosion	Deformation	Deposition or Erosion	Deformation
Miocene	Upper	Early basic breccias (widespread)		Basic tuff (?) (local)		(?)	
Miocene	Lower	Erosion		Erosion (?)		Erosion (?)	
Oligocene		Erosion		Erosion		Erosion (?)	
Eocene	Upper	Erosion	Normal faults (local)	Erosion	Normal faults (local)	Erosion (?)	Heart Mountain overthrust
		(Unconformity (?))	Heart Mountain overthrust	(Unconformity (?))	Heart Mountain overthrust	(?)	
Eocene	Middle	"Early acid breccia" (local)		Andesitic tuffs (local)		Andesitic tuffs (?) (local)	
		(Conformity)		(Conformity)		(?)	
Eocene	Lower	Border Wasatch (local) Erosion		Border Wasatch (local) Erosion		Bighorn Basin Wasatch { Tatman Mtn. beds, Lost Cabin beds, Lysite beds, Gray Bull beds, Sand Coulee beds } Subdivisions of Sinclair and Granger	Local depression
		(Unconformity)		(Unconformity)		(Unconformity (?))	
Basal Eocene ("Paleocene")			Extensive normal faults Large folds Widespread uplift		Local normal faults Small folds Local uplift		Depression
Basal Eocene ("Paleocene")		Fort Union (?)	Sinking (?)	Fort Union	Widespread sinking	Clark Fork beds of Sinclair and Granger Fort Union	Widespread sinking
		(Local unconformity)	Local warping	(Local unconformity)	Local warping	(?)	(?)
Tertiary (?)[1]		Lance formation (?)	Sinking (?)	Lance formation	Sinking	Lance formation	Sinking

[1] The Lance formation is here placed in the Tertiary (?) to conform with the usage of the U.S. Geological Survey, although the local evidence indicates conformability with the underlying cretaceous beds.

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SUMMARIES OF PRE-CAMBRIAN LITERATURE OF NORTH AMERICA

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INTRODUCTORY

In 1915, summaries of pre-Cambrian literature from 1909 to 1915 were published in the *Journal of Geology*. The summaries published herewith bring this review nearly down to date. For 1919, attention has been given only to those publications which are likely to contain important papers on the pre-Cambrian. Emphasis in these summaries is placed on stratigraphic facts and problems.

I. LAKE SUPERIOR REGION AND ISOLATED PRE-CAMBRIAN AREAS OF THE MISSISSIPPI VALLEY

In the Lake Superior region notable contributions to the stratigraphy of the pre-Cambrian have been made by Wolff, Grout and Broderick, Hotchkiss, and Allen and Barrett. The tendency has been to subdivide the iron formations of the leading districts into several units and to connect the occurrence of major ore deposits with certain of these units. In the main productive portion of the Mesabi district, Wolff from his extended experience in drilling and mining has recognized four divisions of the Biwabik iron formation. Grout and Broderick have recognized similar units in the eastern, less-productive portion of the formation. Hotchkiss has found an unconformity in the Ironwood iron formation of the Gogebic district and has recognized two units in the upper division and three in the lower. He has also found an unconformity between the iron formation and the overlying Tyler slates. The recognition of these new unconformities, Hotchkiss believes, does not call for a revision of correlation. Allen has discovered an unconformity cutting the Upper Huronian

formations of Van Hise and Leith in the eastern part of the Gogebic district. Between the Keweenawan and this unconformity, Allen finds a series of clastic sediments which are neither Keweenawan nor Upper Huronian. Allen decides that the Upper Huronian of Van Hise and Leith is to be correlated with the Middle Huronian of the Marquette district. On much less convincing evidence than in the Gogebic district he also concludes that a Middle Huronian is found in the Menominee district. Following these studies, a revised correlation of the Lake Superior region is offered by Allen in which all the important iron formations of the region are designated as Middle Huronian.

Allen has made important studies of the region between the Penokee and Iron River districts, but owing to the drift cover of the area he has not obtained the facts for a satisfactory correlation of the Iron River with the Penokee and Marquette districts. He has also studied the Gwinn district and the eastern extension of the Menominee district.

R. C. Allen[1] believes that the pre-Cambrian rocks of the Gwinn district located about sixteen miles south of Marquette, Michigan, comprise two unconformable series which he correlates with the Upper and Middle Huronian respectively. The succession according to Allen is shown on page 560.

The graywacke and conglomerate near the middle of the sedimentary succession constitutes the evidence on which Allen bases his conclusion for unconformity in the Huronian system. The conglomerate contains fragments which resemble the underlying sediments including iron ore. The two unconformable series appear to be structurally concordant however.

His correlation of the lower series with the Middle Huronian is based on the fact that the Lower Huronian is not known to contain iron formation of the type in the Gwinn district.

Allen and Barrett[2] believe that the acid mica schists of Wolf Lake are the metamorphosed equivalent of the Paint slates of

[1] R. C. Allen, "Correlation and Structure of the Pre-Cambrian Rocks of the Gwinn Iron Bearing District of Michigan," *Jour. Geol.*, Vol. XXII, No. 6 (1914); also in *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 161–64.

[2] R. C. Allen and L. P. Barrett, "The Paint Slate and the Wolf Lake Granite, Gneiss and Schist," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 131–39.

the Iron River and Crystal Falls districts. The granite intrusive into them, they believe, is of the same age as their Presque Isle granite of the Gogebic district. Wolf lake is situated between the Iron River and Gogebic districts.

Quaternary—Pleistocene glacial deposits
Ordovician and Cambrian—limestone and sandstone
Algonkian—Keweenawan, probably represented by certain basic dikes which cut all formations

Upper Huronian Princeton series	Slate, ferruginous slate, chert and quartzite, quartzite	Equivalent of Michigamme slate
	Conglomerate graywacke	Equivalent of Goodrich quartzite of Marquette district
Unconformity Middle Huronian Gwinn series	Gray slate Black slate Iron formation Gray slate Black slate	Equivalent of Negaunee iron formation and Siamo slate
	Arkose Conglomerate	Equivalent of Ajibik slate

Unconformity
Archean system
Laurentian—Granite and greenstone, mainly granite
Keewatin

Allen and Barrett[1] find that the pre-Cambrian rocks at the Little Lake Hills about seven miles east of the Gwinn district of Michigan consist from the base upward of conglomerate, arkose, and quartzite separated by an unconformity from a conglomerate quartz slate and quartzite respectively. The strata appear to be concordant, but the conglomerate near the middle of the column is clearly basal. The lower series is correlated with the Middle Huronian Gwinn series of the Gwinn district; the upper series with the Upper Huronian–Princeton series of the aforementioned district. The absence of iron formation in the Little Lake Hills, Middle Huronian is thought by the writers to indicate the depth of erosion of the Gwinn series before the Princeton series were laid down.

[1] R. C. Allen and L. P. Barrett, "Evidence of the Middle-Upper Huronian Unconformity in the Quartzite Hills at Little Lake, Michigan," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 153–59.

Allen[1] finds a series of magnetic belts in a region covered by Paleozoic rocks and glacial drift extending east of Waucedah on the Menominee range to Escanaba, a distance of about twenty-eight miles. From Waucedah, the buried eastward extensions of two productive iron formations have been traced for six miles by magnetic survey. The detached magnetic belts east of this limit may or may not be equivalent to the iron ranges at Waucedah. They undoubtedly represent belts of folded sedimentary rocks which may include iron formation.

Allen and Barrett[2] describe the Conover district of northern Michigan, about forty-five miles southeast of the Gogebic range, as a drift-covered area showing several magnetic belts. Drilling has shown that the underlying rocks are slates intruded by granites. The authors believe that the slates are the equivalent of the iron-bearing slates of the Iron River district.

Allen and Barrett[3] state that the existence of the Manitowish range is indicated by a series of strong, parallel linear magnetic belts about twenty-five miles southeast and parallel to the Gogebic range. Drilling has shown that the underlying drift-covered rocks are mica schists intruded by granites.

Allen and Barrett[4] report that the Vieux Desert district of Wisconsin and Michigan lying about forty miles southeast of the Gogebic range is a deeply drift-covered area showing several faint magnetic belts. As shown by drilling, the underlying rocks are acid gneisses and schists.

Allen and Barrett[5] correlate the strongly magnetic iron formation of the Marenisco range with the Ironwood formation of the

[1] R. C. Allen, "Relative to an Extension of the Menominee Iron Range Eastward from Waucedah to Escanaba, Michigan," *Econ. Geol.*, Vol. IX, No. 3 (1914), pp. 236–38, 1 map; also in *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15.

[2] R. C. Allen and L. P. Barrett, "Geology of the Conover District," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 123–29.

[3] R. C. Allen and L. P. Barrett, "Geology of the Manitowish Range," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 111–17.

[4] R. C. Allen and L. P. Barrett, "Geology of the Vieux Desert District," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 119–21.

[5] R. C. Allen and L. P. Barrett, "Geology of the Marenisco Range," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 65–86.

Gogebic district. Both are classified by them as Middle Huronian. The succession in the Marenisco range, they state, is as follows:

Keweenawan		Diabase
	Igneous contact	
Huronian	Middle Huronian (Animikie)	Intrusive granite Intrusive greenstone Slate Extrusive lavas Iron formation Quartzite and graywacke
	Unconformity	
Archean	Northern Area—granite and greenstone Southern Area—mica schist, green schist, and amphibolite (may be Huronian)	

The Marenisco range lies three to twelve miles south of and is parallel to the Gogebic range.

Allen and Barrett[1] describe the Turtle iron range about eighteen miles southeast of and parallel to the Gogebic range of northern Wisconsin and Michigan. The succession of the range as stated by the authors is as follows:

ALGONKIAN:		
Keweenawan	Intrusive diabase Granite and greenstone	
Huronian	Middle Huronian (Animikie)	Granite Effusive Agglomeratic and ellipsoidal Greenstone Black slate and graphitic schist Iron formation Quartzite and mica schist
	Unconformity ?	
	Lower Huronian	Mica schist (may be Middle Huronian) Dolomite and dolomitic quartzite Quartzite
	Unconformity	
ARCHEAN:		
Keewatin	Mica schist and green schist	

[1] R. C. Allen and L. P. Barrett, "Geology of the Turtle Range," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 86–109.

Allen and Barrett[1] find that a group of dominantly clastic sediments overlie with marked unconformity the Upper Huronian of Van Hise and Leith in the Gogebic district. They also find that a granite intrudes the Upper Huronian. Their threefold division of the rocks between the Keweenawan and the Archean of the Gogebic, they claim, identifies this succession with the three Huronian divisions of the Marquette district. They designate as Middle Huronian, the Upper Huronian of Van Hise and Leith in the Gogebic district and extend this change to the correlation by these authors to every other district of the Lake Superior region, outside of the Marquette district. The revised correlation table which Allen and Barrett offer places every important Lake Superior iron formation excepting that of the Vermilion district in the Middle Huronian.

In 1919, Allen[2] extended to the Menominee district the threefold classification of the Huronian which he had found applicable to the Gogebic district of northern Michigan. His revised correlation of the Huronian of the Menominee district is shown on page 564.

In previous correlations of the Menominee, notably that of Bayley in Monograph 46 of the U.S. Geological Survey, the Middle and Upper Huronian of Allen were regarded as a conformable succession designated Upper Huronian. Van Hise and Leith, in 1911, recognized a Middle Huronian quartzite, but later Leith is said to have given up this revision. Allen bases his separation of the Upper Huronian of Bayley on the fact that some drill holes have shown what is interpreted as a basal conglomerate between the Hanbury slate and the Curry iron formation. Many drill holes do not show this conglomerate. He also appeals to the fact that the Randville dolomite in different places is covered by various formations ranging from the Traders iron formation to the Hanbury slates. Bayley had accepted one of the alternative explanations for this fact, viz., that the formations overlying the Randville were all conformably deposited on a very uneven surface of the

[1] R. C. Allen and L. P. Barrett, "Contributions to Pre-Cambrian Geology," *Mich. Geol. Surv. Pub. 18* (1915), Geol. Ser. 15, pp. 13–164, 12 pls., 11 figs., maps.

[2] R. C. Allen, "Correlation of Formations of Huronian Group in Michigan," *Am. Inst. Min. and Met. Eng.* (1919), No. 153, pp. 2579–94.

Randville. Allen emphasizes this relation of the Hanbury slate as evidence of unconformity with the Curry iron-formation group. No proof of angular discordance between the Hanbury slates and the Curry iron formation seems to have been found by Allen. His recognition of the Loretto slate is based on the fact that on a certain

Period	Epoch	Stage	Formation
Epi-Huronian	Revolution	Emergent interval	Granite
	Upper Huronian	Quinnesec	Eruptive contact, basic extrusives, sills and dikes
		Hanbury	Great slate series with beds of conglomerate, quartzite, graywacke, ferruginous chert, and impure limestone. Thickness ?
	Emergent	interval	
Huronian	Middle Huronian	Loretto	Slate 400 feet
		Curry	Iron formation 100 to 200 feet
		Brier	Ferruginous, siliceous banded slate 300 to 400 feet
		Traders	Conglomerate, quartzite, and iron formation 150 feet
	Emergent	interval	
	Lower Huronian	Randville	Dolomite, cherty dolomite, and talcose facies 1,000 to 1,500 feet. Conglomerate, arkose, graywacke, and quartzite 1,200 feet
	Great Archeo	zoic interval	

forty-acre lot, a few drill holes passed through what he assumes to be the basal Hanbury conglomerate and then through a slate before striking the Curry iron formation. It appears that Allen's revision is based solely on a very local occurrence of a fragmental rock above the Curry iron formation.

Broderick[1] presents a detailed classification of the beds of the Biwabik iron formation in the eastern part of the Mesabi range. He retains Wolff's general classification into Upper slaty

[1] T. M. Broderick, "Detail Stratigraphy of the Biwabik Iron Bearing Formation, East Mesabi District, Minnesota," *Econ. Geol.*, Vol. XIV (1919), pp. 441–51.

beds, Upper cherty beds, Lower slaty beds, and Lower cherty beds.

Broderick[1] interprets certain negative magnetic lines of the Duluth gabbro as due to a certain angle of inclination of the magnetic formations with the horizontal.

According to Cayeux[2] traces of crinoids are found in the iron formations of the Gogebic, Mesabi and Menominee ranges. They consist of circular, quadrilateral, and hemispherical bodies larger than the oölites and of polygonal cells whose walls are composed of iron. The cells occur with and without alignment.

Grout[3] finds that siliceous pegmatites formed on all sides of the basic Duluth gabbro, but that distinct dikes occur only outside the contact. He infers that the two magmas separated in the liquid state.

Grout[4] presents interesting petrographic descriptions of the Biwabik iron formation of the eastern part of the Mesabi district. He concludes that originally the iron formation was a shallow water deposit formed mainly by organic processes.

Grout[5] proposes the name lopolith for intrusions like the Duluth gabbro whose floors and roof sag downward toward the middle. Evidence is introduced for concluding that the main mass of this intrusion was along a plane of unconformity. Suggestions are made that the method of intrusion of the lopolith is different from that of a laccolith.

Grout believes, as indicated by his diagrams, that the dip of the pre-Cambrian beds around the western rim of Lake Superior is due to settling rather than compression. It would be interesting to find out whether the nature of the fracture and flow cleavage structures in these formations checks with this view.

[1] T. M. Broderick, "Some Features of Magnetic Surveys of the Magnetic Deposits of the Duluth Gabbro," *Econ. Geol.*, Vol. XIII (1918), pp. 35–49.

[2] L. Cayeux, "Existence de restes organique dans le roche ferruginenses associées aux minérais de fer huroniens des Etats-Unis," *Acad. Sci. Paris Compt. rend.*, Vol. 153, pp. 910–12.

[3] F. F. Grout, "The Pegmatites of the Duluth Gabbro," *Econ. Geol.*, Vol. XIII (1918), pp. 185–97.

[4] F. F. Grout, "The Nature and Origin of the Biwabik Iron Bearing Formation of the Mesabi Range, Minnesota," *Econ. Geol.*, Vol. XIV, (1919), pp. 452–64.

[5] F. F. Grout, "Lopolith, an Igneous Form Exemplified by the Duluth Gabbro," *Am. Jour. of Science*, Vol. CXCVI (1918), pp. 516–22.

Grout[1] states that the Duluth gabbro lopolith shows differentiation into the gabbro and granite families and discusses the problem of the processes of differentiation.

Hore[2] presents descriptions of the most important copper lodes of Upper Michigan, and reviews the literature of the region. He concludes that the ores are replacement deposits formed by chloride solutions liberated with the formation of the traps in which they occur or with which they are associated; that they have not been modified except in very minor ways since they were formed; but that the rocks in which they are formed were farther tilted since the ores were formed.

Hotchkiss, Bean, and Wheelwright[3] map a part of the pre-Cambrian area of Ashland, Bayfield, Washburn, Sawyer, Price, Oneida, Barron, Rusk, and Chippewa counties. The chief aim of the work is to show the distribution of iron-bearing formations. Since the area is nearly all drift-covered, magnetic surveys furnish most of the facts. The pre-Cambrian sediments are classed as Barron quartzite and undivided Huronian. Keweenawan traps and granites and gneisses probably of various ages are found in the area. The report has notable chapters on field methods used in work of this type and on the nature and interpretation of magnetic data.

Hotchkiss[4] has made an important contribution to the study of the stratigraphy and structure of the Gogebic iron district of northern Wisconsin and Michigan. The influence of stratigraphy and structure on the formation of the ores is also discussed by him. Many new facts and relationships are presented. Although he recognizes several new unconformities in the succession, he does not believe that the facts now known warrant any fundamental

[1] F. F. Grout, "A Type of Igneous Differentiation," *Jour. Geol.*, Vol. XXVI (1918), pp. 626–58.

[2] R. E. Hore, "Michigan Copper Deposits," *Mich. Geol. Surv. Pub. 19* (1915), pp. 19–161, 18 pls., 16 figs.

[3] W. O. Hotchkiss, "Mineral Land Classification Showing Indications of Iron Formations," *Wis. Geol. Surv. Bull. No. 44* (1915), 378 pp., 8 pls., 39 figs. (incl. maps).

[4] W. O. Hotchkiss, "Geology of the Gogebic Range and Its Relation to Mining Developments," *Eng. and Min. Jour.*, Vol. CVIII (1919), pp. 443–52, 501–7, 537–41, 577–85.

revision of the classification by Van Hise and Leith. The essentials of the stratigraphic classification by Hotchkiss follow:

Keweenawan sandstones and conglomerates overlain by basic flows

Unconformity

Tyler graywacke slate 0–2 miles thick	Graywacke slates Iron carbonate slates Pabst member-cherty and fragmental slate beds

Unconformity

Upper Ironwood formation	Anvil wavy-bedded ferruginous chert member Pence even-bedded ferruginous slate member

Slight unconformity

Lower Ironwood formation	Norrie wavy-bedded ferruginous chert member Yale member—interbedded ferruginous cherts and ferruginous slates Plymouth member—wavy-bedded ferruginous chert (most mines located on this member)

Palms quartzite 400 feet to 800 feet

Unconformity

Bad River cherty dolomite with quartzite below in eastern part of district

Unconformity

Granite and green schist both of igneous origin

The unconformities within the Ironwood formation and between the Tyler slate and the Ironwood formation have not been described before. Their existence is inferred from basal conglomerates and evidences of erosion of the members underlying the unconformity.

Lane[1] finds that the strata on the east side of the Copper range were uplifted and the eastern sandstone deposited on them. The Trap range subsequently overrode the sandstones in places several hundred feet.

Leonard[2] states that pre-Cambrian granite struck in wells of the Red River valley is the only known pre-Cambrian rock of North Dakota.

[1] A. C. Lane, "Abstract," *Bull. Geol. Soc. of America*, Vol. XXIV (1913), p. 718.

[2] A. G. Leonard, "The Geology of North Dakota," *Jour. Geol.*, Vol. XXXVII (1919), pp. 1–27.

Leith[1] suggests that the unconformity at the base of the Cambrian was developed by a process of cut and fill, and that the common occurrence of late pre-Cambrian terrestrial sediments is more than a coincidence, but is related to the development of the basal Paleozoic unconformity.

Nebel[2] presents a petrographic study of certain basal portions of the Duluth gabbro and its contact effects.

Powers[3] reports that drilling in the east-central portion of Kansas has shown the existence of pre-Cambrian granite of considerable relief occurring along a north-south line.

Wolff[4] reports that the average thickness of the Mesabi iron formation is six hundred and twenty feet, and that it consists of four divisions which from the top down are as follows: Upper slaty horizon, Upper cherty horizon, Lower slaty horizon, and Lower cherty horizon. The ores occur chiefly in the two cherty horizons and in the Lower slates. Marked differences exist between the ores of the various horizons.

[1] C. K. Leith, "Relations of the Plane of Unconformity at the Base of the Cambrian to Terrestrial Deposition in Late Pre-Cambrian Time," *Congrès Géologique International,* XII. Session Canada, pp. 333–37.

[2] M. L. Nebel, "The Basal Phases of the Duluth Gabbro Near Gabamichigami Lake, Minnesota, and Its Contact Effects," *Econ. Geol.,* Vol. XIV (1919), pp. 367–402.

[3] Sidney Powers, "Granite in Kansas," *Am. Jour. of Science* (4th ser.), Vol. XLIV (1917), pp. 146–50, 1 fig.

[4] J. F. Wolff, "Recent Geologic Developments on the Mesabi Range, Minnesota," *Am. Inst. Min. Eng. Bull. No. 118* (1916), pp. 1763–87, 14 figs.

[*To be continued*]

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Diastrophism and the Formative Processes. XIII. The Planetesimals and their Infall. By T. C. CHAMBERLIN.

Geologic Reconnaissance of the Southern Part of the Taos Range, New Mexico. By JOHN W. GRUNER.

Summaries of Pre-Cambrian Literature of North America. Papers III–VII. By EDWARD STEIDTMANN.

A Pleistocene Peneplain in the Coastal Plain. By H. F. CLELAND.

The Mineralography of the Feldspars. By H. L. ALLING.
To be published as a supplement to the *Journal of Geology*.

Features of a Body of Anorthosite-Gabbro in Northern New York. By WILLIAM J. MILLER.

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THE

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OCTOBER-NOVEMBER 1920

THE KATMAI REGION, ALASKA, AND THE GREAT ERUPTION OF 1912

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In June, 1912, Mount Katmai was the scene of one of the greatest volcanic eruptions known in history. The material ejected, mostly in the form of pumice and fragmental glass, formed deposits whose total volume has been calculated to amount to nearly five cubic miles.[1] At the town of Kodiak, a hundred miles away, this fragmental material ("ash") fell to the depth of nearly a foot, and nearer to the volcano hundreds of square miles of territory were completely devastated.

General knowledge of the effects of this eruption has been derived chiefly from the explorations of several expeditions sent out by the National Geographic Society, the first one under G. C. Martin and later ones under R. F. Griggs.[2] The expedition of the summer of 1919 was planned on a considerably more ambitious scale than former ones, and an invitation was extended to the Geophysical Laboratory to co-operate in the scientific work.

[1] G. C. Martin, "The Recent Eruption of Katmai Volcano in Alaska," *National Geographic Magazine*, Vol. XXIV (February, 1913), No. 2, p. 131.

[2] G. C. Martin, *Nat. Geog. Mag.*, Vol. XXIV (February, 1913), No. 2, p. 131; R. F. Griggs, *Nat. Geog. Mag.*, Vol. XXXI (January, 1917), No. 1, p. 13; and Vol. XXXIII (February, 1918), No. 2, p. 115; *Ohio Journal of Science*, Vol. XIX (1918), p. 2.

Under this arrangement E. T. Allen, E. G. Zies, and C. N. Fenner joined the party for the purpose of studying the chemical and geological phenomena. Previous to our departure for the Katmai region the publications of Dr. Martin and of Professor Griggs and the information obtained from conversations with them were of much assistance to us in making plans for the trip, and, while we were on the ground, Professor Griggs's knowledge of the region and its phenomena continued to be of great service. The party spent about two months and a half in the field, which is about as long a working season as is practicable.

Since the return to Washington, much time has been given to the study of the materials collected, and a full report will be published later. In advance of such publication, however, it has been thought that a shorter article, descriptive of some of the features of chief geologic importance, may be of interest, and is here presented. Necessarily in this brief treatment, many matters to which attention has been paid in our work will be omitted entirely, and in the case of others the basis for conclusions will be presented in brief form only. Fuller discussion must be reserved for the more comprehensive articles to follow.

TOPOGRAPHY AND GENERAL GEOLOGY

The Katmai country is situated near the base of the Alaska peninsula—that long arm which extends southwestwardly from the southern shore of continental Alaska and, with the Aleutian Islands, reaches nearly to Kamchatka (Fig. 1).

Previous to the eruption of 1912, the Katmai region, though difficult of access, was not entirely unknown. On the Pacific side of the volcanic range was the small native village of Katmai, not more than twenty miles from the volcano. On the Bering Sea slope, at the head of Naknek Lakes, was the similar village of Savonoski. Between them ran a trail which had probably been traveled by the natives for many years, and more recently had been used fairly frequently by white men as a means of crossing the peninsula. In 1898 J. E. Spurr, of the United States Geological Survey, led a party over the Katmai trail, but observed nothing which might be considered to indicate that the preliminary pro-

cesses leading to the eruption were at work except that near the summit of the Pass the party experienced several earthquake shocks. Spurr's record[1] is of much value, however, for the information it gives on the general character of the country. Their route lay through the midst of the area that was subsequently devastated. Further reference to this report will be made later.

FIG. 1.—Sketch map of the Katmai region. By courtesy of the National Geographic Society.

In the Katmai country and its vicinity the volcanic mountains occupy a comparatively narrow strip of territory approximately parallel with the coast line, bounded on both the northwest and southeast sides by areas of predominantly sedimentary rocks. These sedimentary areas exhibit many forms of mountainous

[1] J. E. Spurr, "A Reconnaissance in Southwestern Alaska in 1898," *Twentieth Annual Report, U.S. Geological Survey* (1898–99), Part VII, pp. 31–264.

relief, and the higher summits are but little inferior in elevation to those of the volcanic belt, but dissection has here reached a stage at which broad valleys of moderate slope have been developed.

The line along which arise the active or recently active volcanoes is one of the longest and most clearly defined volcanic chains in the world. At its northeast end the farthermost volcano whose character is definitely known is Mount Redoubt, though Mount Spurr, Black Peak, and Double Peak, from their position and characteristics, appear to prolong the range still farther to the northeast. These all lie well in the interior, among characteristically conti-

FIG. 2.—The Katolinat Mountains, between foot of Valley of Ten Thousand Smokes and head of Naknek Lakes. These mountains show sections of Upper Jurassic shale and sandstone, several thousand feet in thickness, in horizontal strata. Postglacial canyon in foreground. Photograph by J. D. Sayre, 1918.

nental structural features. Thence the range runs southwestwardly to the base of the Alaska peninsula, and follows the latter throughout its length. Here its course lies through a region of nearly horizontal sediments at only a moderate distance from the edge of the continental shelf, but where, at about the end of the Alaska peninsula, the edge of the shelf curves to the northward, the line of volcanoes continues without deviation and strikes off across oceanic deeps of 1,000 to 2,000 fathoms. The Aleutian Islands and their volcanoes form the summits of a narrow, steep-sided ridge, with great depths of water on both sides. The well-defined character and continuity of this volcanic belt were noted by I. C.

Russell, who says: "This belt of igneous activity is nearly 1,600 miles long. . . . It is so narrow and well defined that two parallel lines drawn on a map of Alaska, twenty-five miles apart, may be made to include nearly every volcano in the belt that is known to have been active in historic times."[1]

It seems that such a linear distribution must indicate a major fracture in the earth's crust, and we might expect to find plain

FIG. 3.—View across canyon of Katmai River, from lower slopes of Mount Katmai, looking at Barrier Range. These mountains consist of shale and sandstone, believed to be of Upper Jurassic age, in beds gently inclined away from the observer, with some igneous intrusives. Photograph by D. B. Church, 1916.

evidences of dislocation of strata or even profound disturbances associated with it. On the contrary, very little evidence of this kind is apparent in the region explored by us. On the northwest side of the belt masses of Upper Jurassic sediments (Spurr's Naknek series), 5,000 feet at least in thickness and possibly much more, lie in horizontal, undisturbed strata, whose continuity may often be

[1] I. C. Russell, *Volcanoes of North America*, p. 268.

followed by the eye for miles along the mountain sides. A typical mountain block of horizontal sediments is shown in Figure 2. On the southeast side of the range the sediments are still the shales and sandstones of the Upper Jurassic, little different lithologically or paleontologically from those on the other side. Structurally, however, this fact is observable—that they dip fairly uniformly away from the range at angles of 10 to 15°. Some typical views

FIG. 4.—Looking up canyon of Katmai River from Prospect Point. On the left, Mount Katmai in the background, and its lava slopes and cliffs in the middle distance; on the right, the sediments of the Barrier Range. Just above the river level and at the foot of the lava cliffs, surfaces of glaciated sandstone (shown in Fig. 5) were found. Photograph by D. B. Church, 1916.

are shown in Figures 3 and 4. This difference of attitude of the beds on the two sides of the range may indicate block-faulting and tilting, but this seems remarkably slight evidence to be the only indication of a break of such great length and reaching to profound depths. That profound depths have been reached is indicated by the manner in which the break extends without deviation across fundamentally different surface structures. There is, however, a possibility that the volcanic chain may be situated not directly along the surface trace of the major fracture, but

along a system of accompanying breaks. Such a relation appears to be not uncommon in other volcanic districts.

The Katmai group of volcanoes has evidently been built up on a platform of Upper Jurassic sediments, and several features show that comparatively recent flows have produced marked changes of topography. For instance, the canyon of Katmai River (shown in Fig. 4) is a narrow defile connecting open valleys above and below. It is evident that a former open valley here was invaded by floods of lava coming down from Mount Katmai, which shifted

FIG. 5.—Lava flow of basic andesite overlying glaciated sandstone and a small remnant of till (at pick), at foot of the lava cliffs shown in Figure 4. Photograph by R. F. Griggs, 1919.

the river over upon the lower slopes of the Barrier Range. The river has again cut nearly to grade along a narrow canyon, and beneath the lava-flows may be seen beds of till and sandstone surfaces grooved and polished by glacial action (Fig. 5). In this vicinity lava-flows of apparently post-glacial age measure 1,500 to 2,000 feet in thickness (see Fig. 4).

The lavas of the group of cones that we are considering seem to be predominantly basic andesites. In Mount Katmai itself the succession of flows that have built up the cone is now revealed in the great crater pit, and they appear to be of medium to basic character. The fragments of old rocks thrown out with the new lava in the

recent eruption are likewise of this composition, as are also the materials composing the bowlder beds at the rim of the crater (which probably represent a ground moraine whose components were transported by glaciers from the now annihilated upper slopes of the mountain). The testimony from all sources is concordant and demonstrates with a reasonable degree of certainty that Katmai is predominantly andesitic throughout.

In addition to the lavas that have built up these cones, however, there seem to have been other products thrown out by them. In several places near the lower end of the Valley of Ten Thousand Smokes recent stream-cuttings show peat beds interstratified with many narrow bands of siliceous pumice. Probably the rhyolitic lava ejected in the latest eruption of Katmai was not the first highly siliceous differentiate evolved from the underlying magma.

THE VALLEY OF TEN THOUSAND SMOKES AND ITS GREAT ASH DEPOSIT

According to Spurr's description the portion of the Katmai trail immediately to the northwest of the Pass ran for several miles through a wooded valley of varied topography. During the activities of the eruption, the floor of this valley was covered with a thick deposit of ash and pumice, which in most places has buried every detail of the former topography, and whose surface now forms a gently sloping plain. Thousands of fumaroles have found vent through this deposit and are sending out exhalations of hot gases and vapors. Professor Griggs, who discovered and described these remarkable features, has given to this valley the name "Valley of Ten Thousand Smokes" (Figs. 6 and 7).

This ashy deposit covers the old floor of the valley to a great depth (possibly several hundred feet in certain areas) and extends up over Katmai Pass. Its distribution is shown on the map of the valley.

From the very first explorations of the region by the National Geographic expeditions, Professor Griggs recognized that this deposit is quite distinct from the widespread ash-falls due to the explosive ejection of material from Katmai crater, and that it must be accounted for by the operation of other processes. Because of the fact that, when first discovered, certain of its characteristics

were thought to imply that its formation was the result of the extrusion of a mass of semi-fluid mud, this deposit was termed "the great hot mud-flow," and has been so described.[1]

To the Geophysical Laboratory members of the 1919 expedition the evidence seemed opposed to the idea connoted by the term

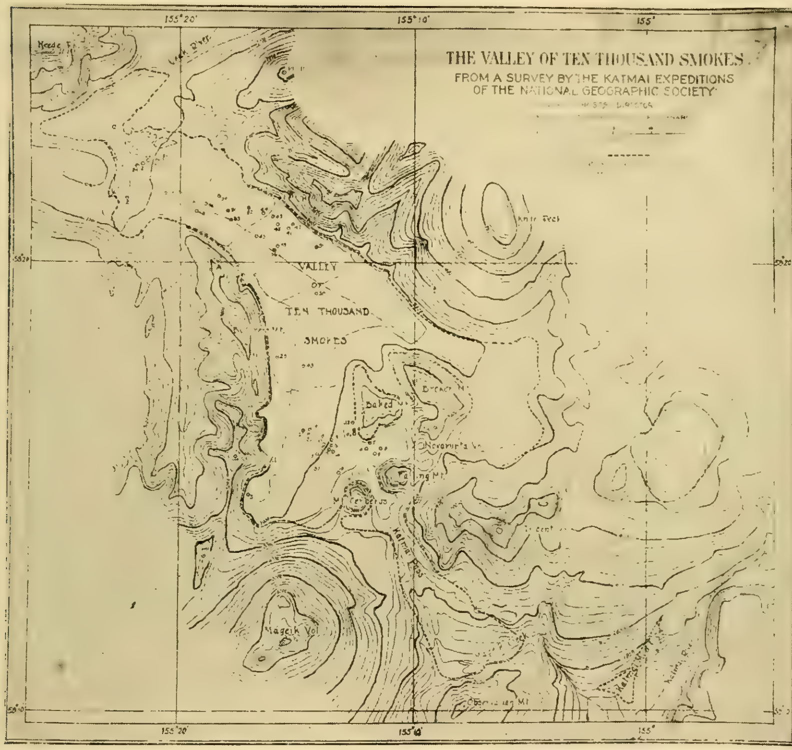

FIG. 6.—Topographic map of the Valley of Ten Thousand Smokes and adjacent region, from surveys made by topographers of National Geographic Society's expeditions.

"mud-flow," and early discussions among us led to the expression of the opinion by Dr. Zies that the evidence was much more in harmony with the idea of the movement of a dry, highly heated mass of sand and pumice than of a water-bearing mud. This

[1] Professor Griggs's article in the *Ohio Journal of Science* (Vol. XIX [December, 1918] No. 2, p. 117) gives an interesting description of this deposit and its remarkable features.

suggestion seemed from the first to have decided merits and later investigations served to strengthen it. Moreover, as evidence of various kinds accumulated, a much more complete conception of the attendant processes was afforded.

The make-up of the deposit itself, its situation with respect to the configuration of the landscape, and various striking effects produced by it demand that certain definite characteristics should be attributed to it at the time of its appearance, and prescribe

FIG. 7.—Looking northerly down the Valley of Ten Thousand Smokes. Photograph by R. F. Griggs, 1917.

rather rigid limitations to one's ideas as to its possible derivation. Observations show plainly that, in the first place, this material was not thrown violently into the air to descend over the general landscape, but that it was restricted very definitely to topographic depressions. In point of time, it was one of the first manifestations of activity, for it is covered by the subsequent ash-falls. The thorough manner in which vegetable material engulfed by it was carbonized and the indications of brush fires started by it can hardly be explained except on the supposition that it possessed a high temperature, probably near incandescence. In many places

adjacent to it but beyond its borders, fallen trees lie as if overthrown by a violent wind accompanying it. This is observable along the margin of the deposit and also on those slopes of the Katolinat Range that lie at the foot of the valley and face up the valley in the direction from which the flow advanced.

Katmai crater could hardly have been its source, as physical obstacles stand in the way of distribution from that point, and

FIG. 8.—The great sand-flow of the Valley of Ten Thousand Smokes, overlain by stratified ash from the Katmai ash-fall; view taken at junction of Knife Creek (at left) and River Lethe (at right, nearly concealed by steam cloud). The stratified terraces just above stream-level are not part of the sand-flow but are the result of recent stream deposition. Photograph by E. G. Zies, 1919.

glaciers that still cover the slopes of Katmai on this side would probably show noticeable effects from the movement of such an incandescent avalanche over their surfaces. The distribution of the material is such that there seems to be almost no escape from the conclusion that it originated within the valley itself and that we must look for its source in vents situated on the floor of the valley or on the lower slopes of the mountains at its head. Such

vents, however, would tend to be concealed by the material that they themselves extruded and by later materials from the ash-falls, and we are not able to point out the exact location of such vents with certainty. It is rather by a process of deduction that our opinions as to their position have been reached.[1]

The vents of extrusion may well have been located along the fissures that are now the seats of fumarolic activity. Support is

FIG. 9.—Carbonized stumps and tundra. The foreground was covered by the sand-flow, but the standing trees in background were beyond its reach. Photograph by E. G. Zies, 1919.

given to this supposition by evidences of former more vigorous activity of a mildly explosive kind at some of these localities. Possibly the newly formed crater of Novarupta in the upper part of the valley was one of the vents, differing from the others only in that it was of larger size than most and that its activity con-

[1] Professor Griggs had previously, in one of his articles, expressed the opinion that the material must have been extruded from fissures within the valley. See article, "The Great Hot Mud Flow of the Valley of Ten Thousand Smokes," by R. F. Griggs, in *Ohio Journal of Science*, Vol. XIX, No. 2, p. 139.

tinued into a stage not represented elsewhere, by which a plug of viscous lava was extruded.

Views of this sand-flow or sand-avalanche and of some of the effects produced are shown in Figures 8–10.

Considering further the origin of the sand-flow, we suppose that rhyolitic magma, charged with dissolved gases, rose to the surface in the newly formed vents. According to general observation the usual course for such a magma is either to retain its gases and form a flow of obsidian, or to evolve them with explosive violence and scatter the disrupted particles to a great distance. In this

FIG. 10.—Trees prostrated as if by wind accompanying sand-flow, though beyond reach of the avalanche of sand itself. Photograph by C. N. Fenner, 1919.

instance, however, it apparently pursued an intermediate course, and produced, by moderately forcible disruption, an outward-spreading and forward-moving torrent of incandescent sand and pumice, each particle of which was surrounded by and partially suspended in gases which it continued to give forth during its impetuous flow.

An artificial reproduction of the properties that are believed to have characterized this ashy material at the time of its extrusion may be obtained by igniting the powder of basic magnesium carbonate. The substance boils in a manner extraordinarily like a liquid, and the gases evolved buoy up the solid particles. In this

condition the mixture exhibits the lack of coherence and readiness to flow that characterize liquids.

The exact counterpart of this deposit does not seem to have been described among volcanic phenomena elsewhere, but the avalanches of incandescent sand and ash that formed prominent

FIG. 11.—Specimen of banded pumice (4×4 inches) from the deposit in the Valley of Ten Thousand Smokes. Adjacent bands show marked differences in composition, as indicated by a silica content of 74.70 per cent in the case of a light band, and 60.40 per cent in an adjacent dark band. The structure is believed to be due to digestion of foreign material.

features of the eruptions of Pelée and La Soufrière in the Antilles in 1902 seem to offer many close analogies. The following quotation from the *Encyclopedia Britannica* gives a statement of the essential features that have been observed in the Peléan eruption:

Its distinctive character is found in the sudden emission of a dense black cloud of superheated and suffocating gases, heavily charged with incandescent dust, moving with great velocity and accompanied by the discharge of immense volumes of volcanic sand, which are not rained down in the normal manner,

but descend like a hot avalanche. . . . . So much solid matter was suspended in the cloud, that it became too dense to surmount obstacles and behaved rather like a liquid.

Though one may find in the detailed descriptions of these sand-avalanches certain differences from the results seen in the area of the valley flow, they seem to be of degree rather than of kind, and the analogies are striking.

Some of the pieces of pumice in this deposit show a banded or variegated structure, such as is illustrated in Figure 11. The difference of composition of adjacent bands is easily apparent, and in the specimen figured, determinations of silica by Dr. Allen have shown 74.70 per cent in a white band and 60.40 per cent in a dark band. It is believed that these structures are due to a process of partial solution of basic rock in the new siliceous magma. The very limited degree of mixing of solutions shown by these specimens hardly permits us to suppose that the solvent action was long continued; therefore we must look for the source in matter which became involved in the magma when it was near or at the surface and just prior to its foaming-up into pumice. There are several possibilities that should be considered. We might suppose that the sedimentary series beneath the valley had been previously injected by rocks of this description and that these were encountered by the new magma and material absorbed from them; or that the floor of the valley was composed of an old lava flow of basic composition, which contributed material; but the supposition that, for a number of reasons, appears to me the most probable is that the source to which we should look is the deposit of lava bowlders of glacial origin that covered the floor of the valley to a great thickness. The fragments of undissolved andesite found with the ash are probably of the same origin, while the pieces of shale that are quite common in places were doubtless derived from the underlying Naknek sediments. All of these may be duplicated in the lava and ejecta of Novarupta.

THE FUMAROLES

The fumaroles, which are now the most active volcanic features of the region, usually find vent through the unconsolidated deposits

that cover the floor of the valley. In most places they are restricted to the valley floor and few are found on even the lower slopes of the adjacent mountains, but the country within a radius of a mile and a half of Novarupta forms an important exception. In this area, hill and valley alike have been greatly shattered, and are crossed by many steaming fissures. This includes not only the portions of the valley to the east and west of Novarupta, but also Baked Mountain, Broken Mountain, Falling Mountain, and some of the lower slopes of Trident. This area was undoubtedly a scene of the greatest activity during the eruption and is still the site of many fumaroles. Evidently the strains that were here set up in the outer crust have been of sufficient magnitude not only to cause fissures to break through the valley floor but also to shatter the adjacent mountains. In most places, however, they are so restricted to the floor that this topographic depression was evidently a controlling factor, and hence a moderate depth for their place of origin is implied. The phenomena suggest what might be expected from the injection of a sill under a rather small thickness of cover.

The fumaroles were the chief subject of investigation by Dr. Allen and Dr. Zies. They made many measurements of temperatures and collected samples of gases for analysis, and much of interest may be expected when their work is completed. At present the account will be confined to a slight description of a few of the features of the fumaroles. In temperature they run from below the boiling-point of water to a heat more than sufficient to melt lead and zinc. The highest temperature found was 645° C. Among the evolved gases, water usually forms more than 99 per cent. The remainder is mostly hydrogen sulphide, nitrogen, carbon dioxide, and methane. Hydrochloric and other acids are probably present, though in small amounts.

Around the vents sulphur is often found in quantities as a sublimation product, and pyrite in finely divided form is very common. Ammonium chloride also has been collected, as well as crystallized hematite and magnetite, and study of the crusts brought home will probably reveal other fumarolic sublimates. The vents are frequently alined along fissures half a mile to a mile

in length. The velocity of the outpouring gases is seldom very high; commonly their escape is attended by a hissing sound at small vents and a subdued roaring at large ones. A close view of a vent of moderate size is shown in Figure 12. It should not be inferred that all of the water that is evolved is of magmatic origin. The ashy and pumiceous material that forms the upper part of

FIG. 12.—Fumarole No. 42. Baked Mountain and Broken Mountain in the background, and the volcanic range in the far distance. Photograph by E. G. Zies, 1919.

the conduits is soaked with water, and considerable quantities must be vaporized and carried out with the hot gases.

FALLING MOUNTAIN

In the upper part of the valley and not far from Novarupta is Falling Mountain, so called from certain remarkable phenomena which it exhibits. Its northerly face is an almost cliff-like slope, probably 2,000 feet in height, which has plainly been produced by recent slumping off of masses of rock. The volume of material thus removed must have been enormous. At the present time blocks or small masses of rock drop off at short intervals and plunge down the slopes with a succession of sharp crashes, and a

talus pile of considerable size has been built up by such accumulations, but this is of insignificant magnitude in comparison with the total quantity that has been lost to the mountain. Strangely enough, there is little hint as to what has become of this mass of rock. The mantle of ash and pumice that covers the floor of the valley at the foot of the mountain spreads its smooth contours over the whole surface. I think we must conclude that the great rock-avalanche at Falling Mountain was one of the first events accompanying the recent outbreak of volcanic activity, and that it occurred under such conditions of forcible disruption and violent movement that the material was spread widely over the valley floor. The subsequent deposits of ash and pumice, which here are of very great thickness, smoothed out the irregularities left in the surface of the transported material. The rock-falls that we now observe are probably of the nature of after-effects. Remnants of the fissures that were formed at the time of the original disturbances now afford passages for gases and vapors from below. Along these channels the andesitic wall-rock has been powerfully acted upon and transformed into porous aggregates of new minerals, whereby the rock rapidly loses its cohesive strength. It is not surprising to find that among the new minerals tridymite is prominent. The conditions are those under which its formation (as a metastable product) is to be expected. A noticeable effect also is the replacement of many of the pyroxene phenocrysts by aggregates of hematite scales.

These alterations seem to be explicable only on assumptions of rather wide-reaching significance. Apparently the gases that permeate the rocks and that manifest themselves at the surface by the slowly rising vapor clouds are capable of reacting with the constituent minerals in such a way as to form volatile compounds, and the porosity indicates that quantities of material have actually been removed by gaseous transfer. The results of similar processes are visible around the vents of many of the fumaroles on the floor of the valley. Here also there is evidence of the transportation of material in the gaseous medium, and we observe the results of reactions induced by rapidly changing conditions of temperature and composition as the gases approach the

outer surface. The most striking result is the deposition of iron compounds around the vents and in the steamy areas—pyrite, hematite, and magnetite—in quantities which, from the observations of Dr. Allen and Dr. Zies, must be very great in total amount.

When there is brought before us in such striking fashion evidence of the ability of these volcanic gases to transport material, we are naturally led to a consideration of the various circumstances attending the evolution of such gases and the effects that are likely to be accomplished. One query that arises is as to the results of the continual outpouring of such great volumes of vapor as rise from the neighboring peak, Mount Martin, and we may ask whether significant changes of composition are not thereby effected in whatever material may lie at the source from which this vapor proceeds, whether it be a body of magma or material of another sort. Unfortunately, insufficient knowledge of the composition of gases rising from the actual throat of a volcano, as well as of their amount and the length of time over which their escape continues, involves the subject in so much uncertainty that definite conclusions as to the quantitative importance of this process are, as yet, hardly warranted.

THE NEW VOLCANO NOVARUPTA

Near the head of the Valley of Ten Thousand Smokes is the site of Novarupta, a small parasitic vent, which evidently was an exceedingly active volcano during the general eruption, and threw out great quantities of fragmental material, chiefly pumice. Much of this is in much larger masses than those thrown out by Katmai. One such projectile, found about a quarter of a mile away, had a diameter of eight feet. The last act of the vent was to extrude a mass of stiff, viscous glass, which, as it was slowly thrust upward, broke into huge blocks. From a distance this pile of steaming lava-blocks, which is about 800 feet in diameter and 200 feet high, resembles an enormous ash heap. It is surrounded by a circular crater-wall composed of ejected fragments, which is much cut up by actively steaming fissures (see Fig. 13). The material of this is mostly pumice and obsidian, but there are also pieces of shale and sandstone and of dense andesite. The question as to the

manner in which this new vent was developed in the floor of the valley is important. There are undoubted evidences of explosive action, but nothing that may not well be attributed to actions going on after the vent had been opened. What we have to account for here is the formation of a rather small, circular orifice, through which a great amount of pumice was ejected and a small amount of lava was extruded, situated in an area which is much

Fig. 13.—Profile of lower part of Novarupta, and a portion of the inclosing crater wall. Photograph by P. R. Hagelbarger, 1918.

fissured but in which other vents of comparable size are lacking. The formation of an orifice of this description is sometimes attributed to the assumed ability of a subterranean body of magma to perforate by explosive action a great thickness of overlying strata and form a cylindrical pipe or conduit (diatreme) for the escape of lava. It is difficult, however, to form a conception of the manner in which such action has been carried out without attributing to the magma properties for which the evidence seems insufficient. It would be necessary to assume not only that an enormous

amount of energy is set free with great suddenness in a narrowly confined space, but that in some manner this force is given a definitely directed tendency upward. The inherent difficulties in this conception are so great that we naturally look for a simpler explanation.

We might suppose, as a second possibility, that the underlying magma possessed great expansive powers because of dissolved gases which were struggling to escape, and was thus enabled to effect an upheaval of overlying material, but the natural result of this would be the upturning of huge blocks over a rather wide area, and the escape of pumiceous material from many widely open fissures, accompanied by the ejection of portions of the fractured blocks in large masses. No such evidence is visible around Novarupta. The ejection of pumice seems to have been confined mostly to a small opening, and there is no hint in the surface contours of the ash that a widespread chaotic upheaval of strata occurred. Moreover, the largest pieces of ejected sediments found were about the size of one's fist. We turn, therefore, to a third hypothesis, which is really the simplest of all: that fissuring was first produced, either because of regional strain or because of hydrostatic pressure due to the injection of a sill; and that the magma rose along such fissures in much the fashion that any liquid might do, except that a certain amount of solution was effected, and that near the surface a sudden conversion into pumice resulted in the violent abrasion of the walls. Under this conception Novarupta would simply represent a channel along one of the fissures, where chance conditions made escape specially favorable and which therefore tended to enlarge the conduit rapidly and establish more direct connection with the body of magma below. It will appear farther on in this article, as various topics are discussed, that none of the phenomena of the Katmai eruption seem to indicate that these magmas exerted great explosive or expansive powers at depths within the earth, and Novarupta conforms to this idea. Undoubtedly explosions of a violent character occurred here after the magma had reached the surface, but no evidence was found of such explosions prior to its ascent.

The banding present in the lava of the dome that now rises above the vent gives very direct evidence regarding the mechanism of its extrusion. This banding is visible at short intervals around the outer circumference of the dome, where masses of rock in place protrude through the general heap of disrupted blocks, and its direction is found to be parallel with the circular outline of the dome. There is also very good evidence of a process of exfoliation of the outer layers as the central core was forced upward.[1] The character of fracture surfaces of the lava-blocks of the dome is

FIG. 14.—"Cornice structure" in Novarupta lava, produced by fracturing and viscous yielding of the hot mass. Photograph by R. F. Griggs, 1919.

interesting. It shows that many of the fractures occurred while the glass possessed properties of both brittleness and viscosity, such as are shown by stiff tar. This resulted in effects of the kind shown in Figure 14, where the surfaces formed by intersecting fractures have become wrinkled and fluted. The term "cornice structure" suggested itself at once as appropriate for such features.

Many bread-crust bombs are found in the vicinity of Novarupta. These were ejected from the crater as masses of non-vesicular, plastic glass, and the vesicularity developed during the

[1] Compare Harker, *The Natural History of Igneous Rocks* (1909), p. 58, Fig. 8.

short interval of time in which the rapidly cooling mass possessed a rigid crust and a plastic interior. The point to be noted is that the magma, rising into the crater from the depths below, did not immediately puff up into pumiceous masses, but accumulated, at times certainly, in pools of non-vesicular lava. The surprising thing is that this condition held in spite of the relief of pressure. On the other hand, we have evidence that under certain conditions very great pressure did not avail to hold the gases in solution. This is furnished by the lava that was later extruded and now forms the dome. In spite of the enormous pressure to which this

FIG. 15.—Mount Katmai, from the Island Camp. The crater pit extends across nearly the whole space between the two summits. Photograph by R. F. Griggs, 1917.

was subjected during extrusion, the contained gases came out of solution and filled the glass with minute vesicles. The explanation of such phenomena as these will be undertaken later.

MOUNT KATMAI AND ITS EJECTA

Let us consider now some of the features of Mount Katmai, and first the form of the crater as it appears since the eruption. The present appearance of Katmai is shown in Figure 15. Before the eruption the height, as shown by the Coast and Geodetric Survey chart, was 7,500 feet. The top of the mountain has now disappeared and an enormous crater abyss has been formed.

Measurements made by Mr. C. F. Maynard, topographer of the 1917 expedition, give the dimensions of this pit as 2 to $2\frac{1}{2}$ miles in diameter and 2,000 to 3,700 feet in depth. About one-half of the area at the bottom is covered by a sheet of water of a peculiar, milky, turquoise-blue or green color, and from near the center of this lake rises a crescentic island. To one standing on the edge of the pit the cliffs appear almost vertical, but their inclination is probably not more than 60° to 70° on the average. They seem to be made up entirely of a succession of lava flows. On the western side of the rim, for about one-third of the circumference, an ice wall appears—a survival of beheaded glaciers, and the depression in the southern side of the rim is floored with bowlder deposits of morainal origin. The bottom of the crater, where not covered by the lake, appears from above approximately flat. At the foot of the cliffs are talus deposits, which appear of rather insignificant proportions. At present the activity is very slight. Steam rises slowly from a number of fissures and clefts near the bottom, and the water of the lake is evidently warm, but on August 10 snow was lying in many places on the crater floor.

The crater of Katmai is a most wonderful and impressive sight, and photographs give but a very inadequate idea of its tremendous proportions (Fig. 16).

A matter of great interest is that of the mechanism by which this huge pit was formed, for this is intimately related to the question of the volcanic processes attending eruptions. Professor Griggs had recognized the importance of solving this problem and had called particular attention to it before our departure for the region. One's first view would naturally be that the material was blown out bodily in the eruption, but there is good evidence that this is not the whole explanation. A remarkable characteristic of the ejected material is the small dimensions of the fragments. Even on the upper slopes of the mountain there are not many pieces above the diameter of a few inches, and a great proportion of them are much finer. Moreover, almost all the larger pieces are of pumice, and the fragments of older rock have a general maximum size even less than the figures given. Also the proportion of these older andesites is rather small, not nearly sufficient

to account for the mass that has disappeared. Their presence is not likely to be overlooked, as their color—dark red to nearly black—renders them conspicuous objects among the accumulations of light-gray pumice. Since this explanation will not account for the total mass of rock that has disappeared, two other possibilities should be considered: first, solution of the older rock in the new magma; and second, crater subsidence.

Respecting solution, it is believed that this process was very active. That this had occurred was suspected several years ago, as specimens of pumice collected by Professor Griggs on former

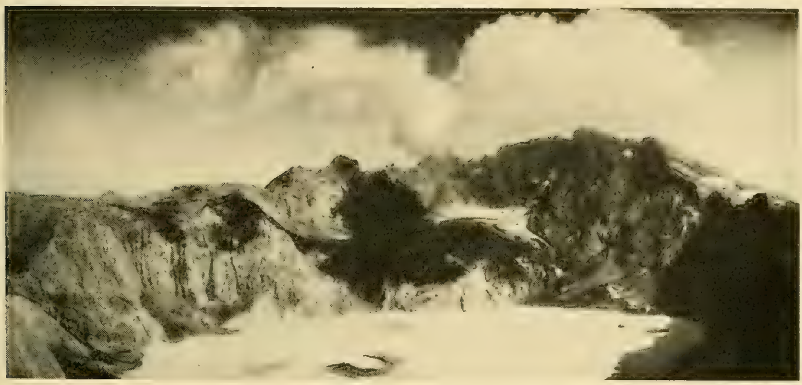

FIG. 16.—The crater pit of Katmai. Topographic measurements indicate a diameter of 2 to 2½ miles, and height of cliffs as measured from the level of the lake as 2,000 to 3,700 feet. Photograph by J. D. Sayre, 1919.

expeditions had been examined microscopically by Professor W. J. McCaughey, of Ohio State University, and the presence of basic phenocrysts in the acid magma and the evidences of instability that they manifested had been noted by him. This has now been confirmed independently and much additional evidence has been secured. Various stages of digestion can be followed until the point is reached where quantities of phenocrysts of hornblende, pyroxene, magnetite, and rather basic feldspar are left undissolved in the glassy matrix. In such instances the original groundmass of the basic rocks has been completely dissolved and the phenocrysts are corroded. Plainly such phenocrysts are out of place in

a rock of the composition of that in which they are found. Moreover, pieces of banded and variegated pumice are common, such as those previously described as occurring in the Valley of Ten Thousand Smokes (see page 583), and are attributed to solution of basic rock in the new siliceous magma just prior to ejection. The evidence on these matters will be discussed more fully a little farther on. It appears to show that the new magma, when it rose into the crater, possessed a sufficient degree of superheat to cause it to attack corrosively the basic rock of the crater walls, and, within a brief period, to effect sufficient solution to permit the dispersal throughout its own mass of the basic phenocrysts derived from great quantities of foreign rock-material. The heat requirements seem to demand that in addition to the original store large accessions should have been received, possibly from rising gases.[1]

In any case a new synthetic magma is believed to have been formed in large quantities. The rapidity of destruction of the walls would be attributed to a combination of the shattering effect of explosions and the corrosive action of magma lying in a pool in the crater. The disappearance of much of the rock of the walls may thus be accounted for. Whether all of it may be accounted for by this process and by the ejection of fragments of undissolved rock is not certain. Further evidence will be obtained from analyses (which Dr. Allen has undertaken) of selected material representative of the new magma, little affected by digestion of basic rock; and of other material, representative of the average result attained by the digestion of foreign matter.

The alternative hypothesis, that of crater subsidence, is one in regard to which little or no direct evidence has been observed. Apparently rock-slides of considerable importance have occurred at several places in the crater, due to the failure of the vertical

[1] Daly's discussion of the effect of rising gases (*Igneous Rocks and Their Origin*, p. 267) is rather misleading. It is true that a bubble of gas, expanding and doing work, loses energy approximately equivalent to the work done, but if the work be expended in producing viscous flow in the surrounding magna, the energy lost by the gas is taken up by the magma, and the system as a whole neither gains nor loses. We may therefore disregard expansion and look upon gas rising from below into a cooler region as a source of heat.

cliff-walls to support themselves, but this may be quite independent of a general subsidence of the floor of the crater. We know from Martin's account[1] that natives who had apparently fled from the region almost at the beginning of the activities reported that the top of the mountain was gone. We should hardly expect crater subsidence to take place at this early stage. On the whole, it seems that this idea should be applied only if the process of solution, which, in any case, seems to have occurred on a large scale, appears quantitatively inadequate to account for all the material that has disappeared. At present it seems best to postpone judgment on this until more information is obtained from the analyses.

EVIDENCE AS TO THE NATURE OF THE ERUPTIVE PROCESSES

A study of the ejecta from Katmai and of the characteristics of the deposits that they form supplies considerable additional information on the eruptive processes. When seen in undisturbed deposits at a distance of, say, eight or ten miles from the crater, the ejected matter forms well-defined strata, such as are shown in Figure 17. The component material is chiefly a light-gray pumice in pieces whose dimensions are three to four inches as an ordinary maximum, and run from this to a very minute size. Mingled with this are specimens of banded pumice, dense obsidian, stony andesites, sedimentary shales, and a sort of volcanic conglomerate. Some of the features of these, and their significance, have been touched upon before but will now be considered in more detail.

It was pointed out, in discussing the great sand-flow in the Valley of Ten Thousand Smokes, that the banded and variegated character of some of the pumice indicated a mixture of basic material with the new siliceous magma shortly before extrusion. In such specimens, sharply defined bands adjacent to each other show such differences of composition as are indicated by Dr. Allen's determination of 74.70 per cent silica in one and 60.40 per cent silica in another. The material thrown out from Katmai crater contains similar specimens. The dark bands consist of partly digested basic rock with large quantities of minerals appropriate to andesites.

[1] G. C. Martin, *Nat. Geog. Mag.*, Vol. XXIV (February, 1913), No. 2, p. 147.

A lack of homogeneity on a somewhat larger scale is indicated by the fact that pieces of pumice from the same stratum of the ash-fall show considerable variation from one to another in the amount of basic phenocrysts they carry. These features are significant. It seems as if turbulent motion in the lava when it was liquid would have destroyed such inhomogeneities, especially the sharply defined banding; hence, that solution occurred subsequent to the

FIG. 17.—The stratified Katmai ash-fall, 8 to 10 miles south of the mountain. Note the sharply defined character of the strata. The heterogeneous material on top is the result of a small landslip since the deposition of the ash and pumice. Photograph by B. B. Fulton, 1915.

rise of the lava and while it was standing in a pool not violently agitated. Evidently the magma did not become inflated at once when pressure was removed in the depths of the earth, but rose as a liquid and stood for a certain period in contact with foreign material upon which it acted corrosively.

A careful study has been made to determine the probable source of this basic material. From samples of the ashy strata taken in the field the pumiceous portion, which is greatly preponderant, has been separated. The residue is found to consist principally of

dark, dense material in small fragments. These, to the number of hundreds, have been studied under a binocular magnifier. Their indentification has not been difficult. Sediments excluded, they consist usually of andesites containing small phenocrysts or groups of phenocrysts of plagioclase, hornblende, pyroxene, and magnetite in a felsitic groundmass. In some, however, the phenocrysts are absent. Most are dense but some are vesicular. In microscopic section the small feldspars of the groundmass are frequently seen to be arranged in flow-lines. It is evident that some of the specimens belong definitely to surface types of rocks and all of them may well be such. The possibility that hypabyssal rocks also may be present cannot be wholly excluded, but no evidence of this origin for any of them has been recognized. In composition they are medium to basic andesites, apparently no different from the rocks that form the walls of the crater pit.

Evidence is at hand regarding the absorption of these andesites by the new magma, but before we proceed to consider this matter it is necessary to digress for a moment.

As previously indicated, it is supposed that the fragments of andesite found in the ash-fall, or at least a large proportion of them, represent wall-rock that collapsed and became immersed in the pool of lava. One might expect, therefore, that similar pieces would frequently be found as inclusions in the pumice. This does not seem to be the case; on the contrary, their mode of occurrence is nearly always as detached particles. This is a matter that requires examination, and several features have been noted which have a bearing upon the subject. It is found, first, that not only are inclusions of andesites rare in the pumice but likewise inclusions of shale and of all other dense material except the phenocrysts; second, many of the fragments, although not now inclosed in pumice, present evidences of previous immersion, such as films of glass adhering to their surfaces, and corrosion effects; third, although the pumice does not carry inclusions, the obsidians, which must have been derived from the same lava-pool as the pumice, carry great quantities of both shale and andesite. From these facts it seems that the conclusion to be drawn is not that the andesites were never immersed in the magma, but that, in

the violent explosions, the frothy, semi-liquid pumice and the dense, rigid andesites reacted differently and were forcibly torn apart. The forms of many of the fragments of andesite are such as to suggest fracture by the explosions. If the forces acting upon them were of such magnitude as to produce fracture, it hardly seems surprising that they became separated from the pumice.

Pieces of obsidian, of ordinary maximum dimensions of three to four inches, and of angular shape, were found everywhere in the Katmai ash-fall within the area of coarse ejecta. Many specimens were collected for study, and they furnish interesting information. It is difficult to conceive any origin for them other than the lava pool that gave rise to the pumice; and the presence within them of pieces of pumice (which would inevitably float on the lava) and their general nature suggest that they represent chilled crusts on the surface of the lava. They contain quantities of inclusions of various kinds: sediments, andesites, other obsidian, pumice, and separate crystals. If it be granted that they are fairly representative portions of the lava, the inclusions they contain "frozen in" in all stages of disintegration are of great instructive value.

Another material present in the ash-fall is evidently closely akin to this conglomeratic obsidian. The matrix is semi-pumiceous to glassy, and the numerous inclusions are of the same sort as those in the obsidian. It is interpreted as a surface scum formed over areas of seething lava. The inclusions in this also have been caught in various stages of disintegration.

From the evidence presented by these specimens, the absorption of xenoliths by the magma seems to have taken place in several somewhat different ways. The chemical composition of the fragments and their porosity were probably important factors in the matter. In some instances peripheral solution, especially of the groundmass, seems to have been the principal process, or well-defined tongues of lava may cut off portions and allow them to float away. Probably a more usual form of attack is one involving an intimate penetration of the whole mass. Several factors may have been involved in this: first, that portion of the groundmass of the rock that consolidated last of all and forms a binding-material

among the grains may have had a melting-range little above the temperature of the new magma, and the penetration of the latter and of its vapors was therefore easy; second, an original vesicularity may have been present; and third, a porous condition may have been developed during the history of the rock. The third feature is important. It is not hypothetical, but rests upon observation, and is believed to have considerable significance. It has been found that many of the andesitic fragments in the pumiceous strata have at some former time undergone a process of alteration similar to that described for the rocks of Falling Mountain. Quantities of minute, glistening scales of tridymite have been formed, and a replacement of ferromagnesian minerals by hematite is observable. This carries several implications: first, these mineral transformations are such as might be expected to result from fumarolic action along fissures in the walls of a crater, but not of the kind that would be looked for at great depths; second, the presence of such fissures and the mineral transformations along them would aid in the collapse of the walls during the activities of the eruption; and third, these altered rocks would be more susceptible to penetration by the magma on their immersion in it.

When the process of penetration of magma into porous xenoliths has been thorough, they appear to have become pasty throughout, and what we find is an irregular, lumpy mass, or clot, consisting of basic minerals in a dark groundmass. Under the microscope the phenocrysts are seen to be much corroded. They often contain a great number of inclusions of brown glass, which fairly riddle them, and they look as if they were disintegrating. The groundmass is essentially glassy but contains a multitude of small, irregular fragments or splinters of crystals, and much brown dust. The low index of this glass indicates an acid material in spite of the dark color, and it seems doubtful whether the amount of material actually fused or dissolved was large; the process was rather one of intimate penetration by the new magma, resulting in separation and dispersal of the component minerals and a partial breaking up of crystal units. The low silica-content found by analysis (as in the specimen illustrated in Fig. 11) and the dark color are probably due to undissolved phenocrysts and dust. When the

penetration by the magma reached a fairly advanced stage before the final inflation occurred, these dark masses as well as the light glass assumed the porous condition; both must have been charged with vapors.

Although, under some circumstances, the bands or schlieren that have arisen from these pasty masses remain sharply distinct for several inches and perhaps much more, it is not unusual, on the other hand, for bands to disappear within a short distance. The facility with which the banding has become obliterated in these cases shows that its sharp definition is not a property that persists in spite of turbulent movements.

In the pumice of the early strata of the ash-fall, phenocrysts are almost lacking; in later strata they become exceedingly abundant. Their appearance at this later stage is ascribed to the setting free of phenocrysts from the andesitic wall-rock in the manner described. Their character in the two environments has been carefully compared. Those in the andesites have been studied in microscopic sections, and also under a binocular magnifier in such specimens as show surface corrosion, which has left them in partial relief. The phenocrysts of the pumice have, many of them, been set free by explosions and occur loose in the ashy strata. These are easily studied with the binocular magnifier. Others, still inclosed within a matrix of pumice or obsidian, have been examined in thin sections. In the andesites the phenocrysts occur both as isolated crystals within the felsitic groundmass and as aggregates of the kind that Judd has called glomeroporphyritic groups, and have certain characteristics in regard to size, form, and grouping. The component minerals are pyroxene, hornblende, plagioclase, and magnetite. In the pumice we find the same minerals, isolated or in the same sort of groups as before, apparently duplicating in all respects the phenocrysts of the andesites.

Let us review briefly the evidence that has been presented on this matter. An immense amount of material has disappeared from the top of the mountain and from the crater walls, and must be accounted for. In the pumiceous strata fragments of andesites are found that have the characteristics of surface-flow rocks, and correspond to what is known of the rocks in the crater walls. The

evidence of fumarolic action that many of them bear is in accord with such a situation. These might account for the rock that has disappeared except that they are quantitatively insufficient. We are left, then, to consider crater subsidence versus incorporation in the new magma. Without trying to decide in this article whether *all* of the material may be accounted for by incorporation, the evidence that a large quantity has been taken up in this manner has been considered. According to this evidence, numerous specimens of andesite show attack. The processes involve either an intimate penetration and consequent softening of the whole mass, followed by dispersal of the phenocrysts; or the breaking up of the fragments by attack along fissures, simultaneously with solution of the groundmass around the periphery of the fragments and eventual setting free of the phenocrysts. Finally, multitudes of phenocrysts of the kind that the andesites carried are found to appear in the later strata of the pumice, though the earlier strata are practically free from them. Their instability with respect to their surroundings is indicated by the active disintegration that they are undergoing. The fact that quartz phenocrysts properly belonging to the magma have no association with them is also significant. These facts taken together seem to form strong evidence identifying the phenocrysts of the pumice with those of the former wall-rock, and the disappearance of large quantities of wall-rock is thereby accounted for.

Some of the materials in the ash-strata deserve further attention. The obsidians that have been described, when heated in the laboratory, swell up to a frothy white pumice closely resembling the pumice found in the field. When their powder is heated in a closed tube it yields water, hydrogen sulphide, hydrochloric acid or a chloride, and some gas having a fetid organic odor. It is planned to investigate these gases with care.

Although many phenocrysts of extraneous origin are found in the pumice, the only phenocrysts that properly belong to the magma are quartz and acid plagioclase. These had probably crystallized out before the magma rose into the crater. The quartz, which is easily recognized, is never associated with the groups of xenocrysts mentioned, but, on the contrary, is found in the purest rhyolitic

phases of the pumice. Its presence supplies information regarding the upper limit of temperature within the magma chamber just prior to extrusion. The transition point between quartz and tridymite at atmospheric pressure is 870° C. Probably great pressure will have a perceptible effect in shifting the inversion-point—a thickness of 20,000 feet of rock strata might possibly raise it 100°—but we can be fairly sure that a temperature of less than 1000° prevailed.

The distinctly stratified form of the ash-fall, with its indications of a waning and renewal of activity many times repeated, harmonizes with the other evidence presented that the melted rock accumulated in a pool in the crater rather than that it was discharged as a continuous stream as soon as some hypothetical obstruction, which had previously restrained its escape from the depths, was removed.

From the evidence that has been brought together certain deductions may now be made. We see that the magma, as it issued from the depths of the earth, did not at first show a tendency to evolve its gases explosively; that is, did not have an extremely high vapor-pressure; but that this was developed after a short period of standing under the new conditions, and explosive eruptions ensued. From this we conclude that in the enormous change of conditions consequent upon rapid extrusion internal equilibrium did not keep pace with external changes, and that prior to extrusion such internal combinations prevailed that the tendency of the gases to escape was not extremely great.

As an indication of the depth in the conduit at which explosions occurred the relative amounts of the various sorts of foreign material ejected with the pumice is of interest. Pieces of andesites from the crater walls are very common; fragments of shale and sandstone from the sedimentary platform are frequently found, but the quantity is not so great as of the andesitic rocks; and pieces of deep-seated granitoid rocks are almost lacking, though a few specimens were found. This relative abundance seems to show that the violently explosive action was exerted only at the surface or at a moderate depth in the conduit.

If the renewal of activity at this vent after a long period of quiet were due to an accumulation of imprisoned forces until they reached a magnitude where they were capable of blasting away

obstructions, the bottom layer of ejecta should be made up largely of material from such a source. As a matter of fact this bottom layer is essentially pumiceous and actually appears to be more nearly free of foreign material and more nearly of rhyolitic composition than any layer above it. The view that the close of a period of activity at a volcanic vent is attended by the formation of a plug of lava which seals up the conduit and that the renewal of activity necessitates the clearing out of such a plug, finds little to support it here. Nor, I think, does a consideration of events in certain other explosive eruptions lead to views different from those expressed for Katmai. Many instances might be cited in which for months previous to a paroxysmal eruption manifestations have occurred, such as outbursts of gas and ashes, that can hardly be looked upon otherwise than as indicating a quite direct connection between the surface and the subterranean activity. It seems not unusual, too, for lava to appear in the crater and remain comparatively quiet for a certain period before explosive inflation occurs. The great eruption at Krakatoa in 1883 seems to have followed such a course.[1] At Pelée also there were premonitory symptoms, consisting of an increased evolution of vapors, at times mixed with cinders; later the moderately explosive (though immensely destructive) ejection of the *nuées ardentes*, accompanying the rise of lava in the crater.[2] A somewhat similar course of events may be found in Koto's description of the eruption of Sakura-jima.[3] By what means a volcanic vent can remain sufficiently open to permit a free escape of vapors, without allowing magma to issue, and what conditions finally bring this period to a close and cause a body of gas-charged, actively corrosive magma to appear are matters whose explanation presents many difficulties. No theory of volcanism that I have seen appears at all adequate to account for the phenomena. Indeed, some of the fundamental concepts of current theories seem irreconcilable with them.

Objection may be raised to the somewhat novel idea that has been presented here, of a state of unstable equilibrium of the

[1] J. W. Judd, "The Eruption of Krakatoa and Subsequent Phenomena," *Report of the Krakatoa Committee of the Royal Society*, pp. 11–20.

[2] A. Lacroix, *La Montagne Pelée et ses Eruptions*, pp. 35–39.

[3] B. Koto, *The Great Eruption of Sakura-jima in 1914*, pp. 56–82.

magma, and the question may be asked as to what combinations are supposed to be entered into between the volatile and non-volatile constitutents that would give the required effects, also as to the nature of the changes in the physical environment by which the condition of unstable equilibrium is brought about. These are natural queries, and answers would be eminently desirable; nevertheless, it is believed that the case rests not upon the ability to answer them but rather upon the plain evidence of the phenomena themselves. It may be of assistance, however, to a comprehension of what is meant by unstable equilibrium of the magma, to consider certain familiar phenomena exhibited by obsidians. Any obsidian which, when heated, puffs up into pumice, shows characteristics allied to those that I have ascribed to the Katmai magma. The behavior of the obsidian in this respect indicates that it likewise in its past history underwent changes of condition in which internal equilibrium failed to keep up with external changes. If this were not true it could hardly have retained its dissolved gases but would have evolved them during cooling. In instances of this kind the lack of equilibrium continued even beyond the stage which the Katmai lavas reached, and finally all possibility of evolving gases disappeared because of increasing rigidity, but this result was probably due to factors (such as rate of cooling) which may well be variable. In the case of Katmai and other volcanoes, it seems reasonable to suppose that the magma first experienced very rapid change of conditions during its rise in the conduit, but then remained for a certain period in comparative quiescence, and thus opportunity was given for approximate equilibrium to be reached before a condition of prohibitive rigidity had set in.[1]

From evidence of the kind given it appears that examples of unstable equilibrium in magmas, due to sudden changes of environment, are not at all uncommon. Recognition of this fact and of what it connotes may be helpful in directing inquiry into the conditions that have brought it about.

[1] Interesting examples of the effect of rate of cooling upon the final product in somewhat analogous systems are furnished by Morey's experiments on hydrated alkali silicate melts prepared in steel bombs. Rapid quenching gave a rigid, hydrated, unstable glass, while slow cooling caused the expulsion of dissolved water and the formation of a pumice. See G. W. Morey, *Jour. Amer. Chem. Soc.*, Vol. XXXVI (February, 1914), p. 226.

SUMMARY AND CONCLUSIONS

A preliminary account has been presented of observations made by the writer as geologist of the expedition sent in 1919 by the National Geographic Society, in co-operation with the Geophysical Laboratory, to the Katmai region. As a result of this work many of the observations made by the director of previous expeditions have been confirmed and supplemented. With regard to one or two others, somewhat different interpretations are given in this article from those of previous publications, but it is believed that on these matters also all concerned are now in agreement. With respect to still other phenomena, which had not been previously described, evidence has been found that affords a basis for extending considerably our ideas respecting the processes at work during the eruption.

It has been found that the volcanoes of this region, which form a continuation of the Aleutian loop or festoon, are situated in an area of sedimentary rocks remarkable for the absence of folding or obvious faulting. The more recent lavas are basic andesites, contrasting greatly in composition with the highly siliceous rhyolite of the last eruption.

In the area of the Valley of Ten Thousand Smokes, it is believed that the injection of a sill or closely similar body of magma into the underlying strata at the beginning of the eruption caused shattering of the rocks above it, and these openings permitted the ascent of magma. The extrusion and inflation of this magma gave rise to a great ash- or sand-flow, analogous in many respects to the *nuées ardentes* of Pelée and La Soufrière, and led to the formation of the parasitic cone of Novarupta. The fumaroles are thought to be due to the continued evolution of volatile constituents from this body of magma. The development of the new vent of Novarupta is ascribed to the enlargement of a channel along one of the fissures. The later extrusion of the stiff lava forming the dome of Novarupta is found to have been similar in many respects to that of the "spine" of Pelée.

At Falling Mountain the most interesting features are those resulting from fumarolic action. Evidence of a process of solution and transfer of rock material in the gaseous medium was found

here, and the results of similar processes around the vents of the fumaroles in the valley were observable. It is suggested that the properties of the evolved gases indicated by this gaseous transfer may at times lead to results of great importance in volcanic processes.

A study has been made to determine the manner in which the top of Mount Katmai disappeared and the great crater pit was formed. It seems quite certain that the material was not blown out directly but must be accounted for otherwise. Crater subsidence may have been a factor, but it is believed that collapse of the crater walls and incorporation of the material in the new magma were chief features. It is recognized that the latter process demands a large quantity of heat for its accomplishment, and the magma evidently was not at a very high temperature prior to its ascent; therefore accessions of heat seem to be demanded. A considerable problem is thus presented, but it does not seem at all insuperable, and it is believed that the evidences of solution are so strong that they cannot be disregarded.

One of the important features of the eruption brings up for consideration a phenomenon to whose significance little attention seems to have been paid hitherto. It is that of a gas-charged magma gradually developing the explosive condition after some interval has elapsed subsequent to its ascent from the depths. The Katmai magma seems to have followed this course, and the phenomenon is apparently not uncommon. This is believed to have great significance and to imply changes of physical environment during its ascent, effected with such rapidity that internal readjustments were not able to keep pace with them. Many of the current theories of volcanism are based upon a fundamentally different conception of the nature and properties of the magma. It is thought that it may be advantageous in many cases to consider matters from the new standpoint here suggested.

In other matters also, theories that have been proposed and somewhat widely accepted are apparently not in accord with the evidence found here. It has not been possible in this article to discuss these matters exhaustively, and other matters of interest have not been touched upon. Fuller treatment will be presented in articles to follow.

July, 1920

ON SOME PHYSICAL PROPERTIES OF ICE

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INTRODUCTORY NOTE BY T. C. CHAMBERLIN

While many of the more obvious problems of ice and ice action have been solved in a general way, there remain not a few questions of a more refined sort which require solution before glaciology can rest on a secure foundation. Some of these questions are critically important for they bear radically on interpretations that have already been widely accepted and are currently taught. More extended and more critical field studies are required to solve some of these questions while the solution of others depends on more discriminative and exact laboratory experimentation. All of them call for more searching analyses of the problems themselves, as a source of guidance in field work and in experimentation, as also in the interpretation of results. The glacialists working at Chicago have been trying to do their bit toward the solution of some of these problems and have had under way for some time a series of attacks along several lines in both field and laboratory. This paper presents the preliminary results of a careful series of laboratory determinations carried out by Professor Motonori Matsuyama, of the Department of Geophysics of the Kyoto Imperial University, Japan, who has been spending the year at Chicago.

When McConnell, followed by Mügge, announced that ice crystals are minutely laminated in planes normal to their optical axes and that movement along these planes was notably easier than in other directions, it was felt by many that these disclosures offered a happy solution of the anomaly of glacial movement which seemed to be a quasi-fluidal flow in a body obviously rigid. But later critical studies raised serious doubts as to the actual participation of the gliding planes in ordinary glacial motion, and so the subject came to demand more refined examination. Up to date, no one, so far as I know, has determined what is the measure of the resistance to motion along these planes compared with the stresses actually brought to bear upon them in ordinary glacial motion. Nor has it been shown whether the relation of these gliding planes to one another is of the elastic or the viscous order. But even if these properties were known, there would still remain the radical question whether glacial motion actually takes place by means of movements along these planes—or in any other way *within* the constituent crystals—or whether it is essentially a motion between the constituent crystals. There are here

therefore two quite distinct problems. The investigations of Professor Matsuyama relate to the second of these.

The method of Matsuyama is, so far as I know, unique in that he deals with bundles of crystals which have a common known orientation. He thus brings movement along the gliding planes into experimental competition with movement between the crystals. All are familiar with experiments upon the yield of glacier ice where the mass under test was formed of many crystals of *diverse* orientation, but this very diversity of orientation stood in the way of a strict interpretation of the results. Matsuyama, however, so selected his prisms and cylinders as to force an alternative between combined movement on gliding planes and movement between the crystals. His method and his achievement are therefore notable.

It is further to be observed that in his experimentation he used the torsional method, following Michelson, in which the errors arising from the stretching or compression of the prisms or cylinders are avoided, since the cross-section remained constant throughout the trial. But as check upon the results of torsion, Matsuyama added the method of bending in which stretching on one face and compression on the other were involved. In the interpretation of the results of this method he called in the resources of the petrographic microscope with the discriminating results given in the text.

INTRODUCTION

The motion of an ice sheet along the mountain slopes and over a large area of the Continent may be caused by more or less different forces. Besides the external forces, it is also important to know what is the behavior of the ice itself in such motion. Numerous works have been published on these problems, among which those of McConnell and Mügge are famous and have been referred to by many authors. According to them an ice crystal can be sheared more easily in the direction parallel to the basal plane than in any other direction. The elaborate works of the members of the Cornell University geological staff[1] added important contributions to the same line. Their idea is that the gliding planes of ice crystals arranged parallel to their basal sections control the behavior of an ice mass as the main factor.

Deeley[2] calculated the viscosity of ice from Main's experiment and found its value to be 6×10^{12} c.g.s. at $0°$ C., while his own observations on Swiss glaciers gave 125×10^{12} c.g.s.

[1] R. S. Tarr and J. L. Rich, *Zeits. f. Glets.*, Vol. VI (1912), pp. 225–49; R. S. Tarr and O. D. von Engeln, *Zeits. f. Glets.*, Vol. IX (1915), pp. 81–139; O. D. von Engeln, *Amer. Jour. Sci.*, Ser. 4, Vol. XL (1915), pp. 449–73.

[2] R. M. Deeley, *Geol. Mag.*, New Ser. 5, Vol. IX (1912), pp. 265–69.

Various investigations related to glacier problems were planned and worked on for many years in this department by Professors T. C. Chamberlin and R. T. Chamberlin. The present work is a part of that series and gives the result of preliminary investigations on the elastic properties of ice. Since torsional force applied to a circular rod is the only type of strain, as Professor Michelson[1] says, in which the cross-section remains constant, the main part of the present study consists of observations on torsional deformation. Later some attempts were made to determine the Young's modulus and also to observe what would happen in bending.

The preliminary work was begun early in the autumn of 1919, but owing to a delay in securing certain necessary apparatus, it was not until about the beginning of February, 1920, that the work really began in earnest. About the end of March it became so warm that it was no longer possible to continue the work on ice. Because the time available for this cold work was so short, the results are to be considered only as preliminary; yet they were so suggestive that the present writer considered it worth while to publish them even with these limitations.

During the research, Professor R. T. Chamberlin took constant interest and gave important suggestions for which the writer is very much obliged.

LIMIT OF ELASTICITY

According to Professor Michelson,[2] the deformation of an elastic body passes through four different stages as it goes on, and in the first portion the deformation is characterized by being approximately proportional to the stress. The limit of this part is well defined in some materials while in others it is not so distinctly marked.[3] The following description will show that ice also has a rather well-defined limit of elasticity in some cases at least.

Method.—In the present experimentation a circular rod of ice was held horizontally with its one end fixed to a rigid stand and the other end attached to a circular disk of radius 7.45 cm. movable

[1] A. A. Michelson, *Jour. Geol.*, Vol. XXV (1917), p. 405.

[2] *Ibid.*

[3] A. E. H. Love, *The Mathematical Theory of Elasticity*, p. 112.

around a knife-edge at its center which rested on a horizontal plane. The whole equipment was kept in a thermos box, the temperature inside of which could be kept low and constant by using freezing mixture. The torsional stress was applied by putting weights on the scale pan hanging from the limb of the circular disk through the bottom of the box. The amount of torsion was observed by means of a telescope through a window in one side of the box.

In the first set of experiments, the test piece was cut out from artificial ice and consisted of parallel crystals with their optic axes transverse to the longer dimension of the bar. The first bar was 13.15 cm. long and 1.73 cm. in mean diameter.

The deformation was found to depend upon the rate of increase of force, especially near and beyond the elastic limit. In the first experiment the force was increased by adding two pieces of weights, each weighing 4.40 gm., every five minutes. The total time duration for this observation was 3.5 hours and meanwhile the temperature was constant at $-7°0$ C. The observed relation between the weight and deformation is shown in Figure 1.

From this curve one can easily see that a rather marked change of yielding is recognizable at the point *B*, up to which the strain is more or less proportional to the stress. This feature is none but the characteristic of an elastic curve[1] and we may say that ice behaves like an elastic solid.

Later it was learned that the point *B* was not so well defined in some cases as in the present one. It is for further study to see when this point will be sharply shown and when not.

MODULUS OF RIGIDITY

Rigidity is the resistance of a material to shearing force and is given by the ratio of the amount of shear to the applied force. If a circular rod of length l and radius a is twisted through an angle Φ by an external couple PL, the modulus of rigidity n will be given[2] by

$$PL=\tfrac{1}{2}\pi n\frac{\Phi}{l}a^4.$$

[1] Given in every book on elasticity.

[2] Poynting and Thomson, *Properties of Matter*, p. 79.

It was found that it took about 10 minutes to reach the new equilibrium position when an ice bar is twisted by a certain stress within the elastic limit. The deformation in the foregoing observation in the part *AB*, therefore, must be slightly modified for this effect. Careful observations were made, increasing the load by the same amount at intervals of 20 minutes. As the result it was found that the mean deviation was 5'.2 per 26 gm. on the

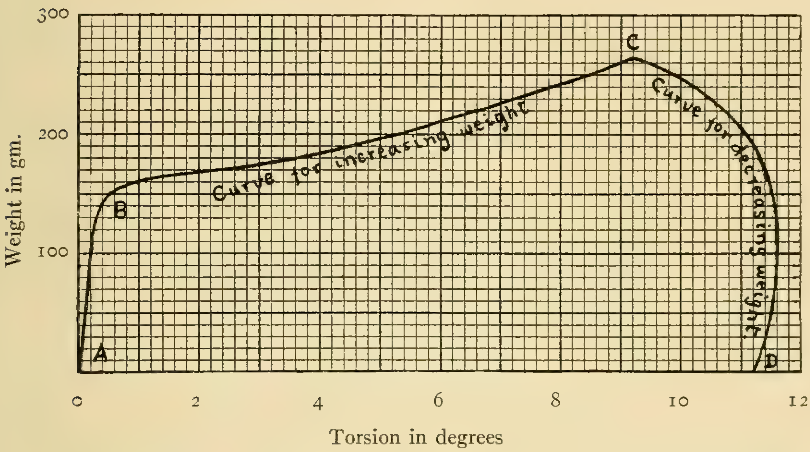

FIG. 1.—Torsion curve of an ice bar, 13.15 cm. long and 1.73 cm. in diameter, with crystals transverse to its longer dimension. Arm of the torsional couple 7.45 cm. Temperature $-7°.0$C.

scale pan, the temperature being kept at $-7°.5$ C. From this and other known values of the constants, we obtain

$$n = 1.9 \times 10^6 \text{ c.g.s.}$$

The value of n was calculated from data in several experiments intended primarily for other purposes. The following table gives the values of n thus obtained for ice bars with optic axes of their component crystals transverse to them.

Temp. (C.)	$n \times 10^{-6}$	Temp. (C.)	$n \times 10^{-6}$
-11.7	2.0	-9.3	2.1
-11.7	2.0	-7.5	1.9
-10.0	1.6	-6.7	1.6
-10.0	2.1	-6.7	1.6
-9.5	2.0	-4.0	1.6

These results seem to show some decrease of rigidity with rising temperature. Near the melting-point of ice, its rigidity will decrease more rapidly than at lower temperatures, so that the rigidity-temperature curve will be concave toward the temperature axis. If we consider rigidity to depend upon the temperature t up to the second power and calculate the coefficients from the foregoing data, we obtain

$$n=(0.18-0.095\,t-0.0020\,t^2)\times 10^6 \quad \text{c.g.s.}$$

This is represented by the curve in the following figure (Fig. 2), the observed points being denoted by crosses.

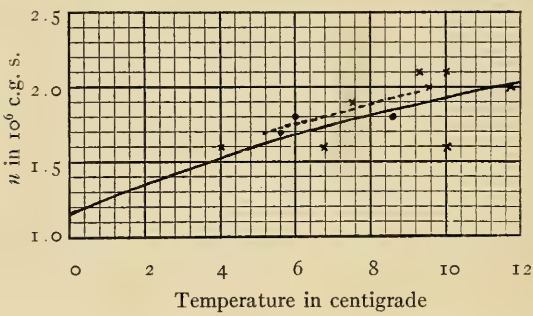

FIG. 2.—Modulus of rigidity of ice composed of parallel crystals at various temperatures. Crosses denote the values when shear is parallel to the optic axes of the crystals and dots the values when shear is parallel to their basal sections.

Similar observations were made for ice bars with the optic axes of the constituent crystals parallel to the axis of the bar. The test piece was 20.95 cm. long and 1.93 cm. in diameter. The crystals were for the most part several millimeters in diameter and never so long as to reach from one end of the bar to the other. The mean deviation was 10′ by 44.0 gm. at $-6°.0$ C. Using the known values of the constants, the rigidity was calculated to be

$$n=1.8\times 10^6 \text{ c.g.s.}$$

The following table gives the value of n determined from different experiments:

Temp. (C.)	$n\times 10^{-6}$
−9.2	2.1
−8.6	1.8
−6.0	1.8
−5.6	1.7

These data are, by no means, sufficient to determine the relation between the temperature and the rigidity, or to compare this case with the former. As a very rough approximation, however, if we take the means of the first two and the last two and join the points corresponding to them in the figure, we will see that the joining line lies above the curve for the ice bar with transverse crystals. This at least suggests that an ice mass will be deformed more easily when it is twisted parallel to the optic axes of the constituent crystals than when twisted parallel to their basal sections.

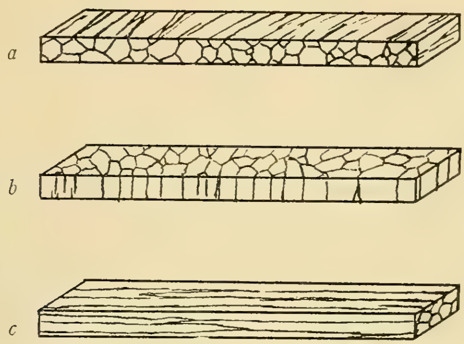

FIG. 3.—Orientations of crystals in test specimens for bending

tions. This result alone is not much to be relied upon. But it is consistent with the results which will be described later.

YOUNG'S MODULUS

Elastic behavior of a solid is determined by two independent elastic constants. We have already found the value of the modulus of rigidity of ice. It is desirable to find also the other, or Young's modulus, which is the resistance of a wire to elongation defined as the ratio of the stress to the strain. To determine this, the usual method of bending was used, with two mirrors and the scale-and-telescope method.[1]

The test specimens were bars of ice with rectangular cross-section (Fig. 3). The component crystals were arranged either (*a*) horizontally or (*b*) vertically transverse to the bar, or else

[1] Poynting and Thomson, *Properties of Matter*, p. 100.

(*c*) parallel to the length of the bar. Since, as we will see later, ice is affected by the phenomena of elastic fatigue, a new bar was generally prepared for each experiment. These bars were not always of the same magnitude; the bar 1*a* was made by cutting bar 1 in half to see if we could get the same result. The results of several observations are given in the following table:

Specimen No.	Orient.	Length cm.	Width cm.	Thickness cm.	Temp. (C.)	Young's Mod. 10^6 c.g.s.
1..........	*a*	31.0	1.58	.95	−5.0	11.2
1*a*..........	*a*	15.0	1.58	.95	−4.8	10.5
2..........	*a*	18.0	1.87	1.05	−2.0	6.0
3..........	*b*	22.5	1.73	.85	−3.0	6.0
4..........	*b*	18.0	1.80	1.02	−2.2	5.9
5..........	*c*	22.2	1.62	.83	−4.0	18.9
6..........	*c*	11.0	1.25	.76	−4.1	16.6
6*a*..........	*c*	11.0	1.25	.76	−3.0	20.0

It will not be safe to consider the effect of temperature upon Young's modulus in each case from these few determinations. Since the range of temperature in these observations is not very large, we may consider the mean values for each case not very far from the truth. These mean values are:

Orient.	Temp. (C.)	Young's Mod. 10^6 c.g.s.
a............	−3.9	9.2
b............	−2.6	6.0
c............	−3.7	18.5

Here it is clearly shown that the specimens of orientation *c* whose crystals are parallel to the long dimension of the bar have the largest value of Young's modulus. We have already seen that the modulus of rigidity seemed greater when shear is parallel to the basal section of the constituent crystals than when perpendicular to it. These results have very important meaning in considering the behavior of an aggregate of ice crystals. If the gliding planes of an ice crystal parallel to the basal plane are the main factor determining the behavior of an aggregation of ice crystals under deforming forces, we must expect that ice will be deformed

most easily when the deforming force is parallel to the basal planes of the constituent crystals. The present result shows the reverse fact which suggests that there must be some other factor controlling the deformation.

It is interesting to compare the values of elastic constants of ice with those of other materials.[1]

Material	Rigidity	Young's Mod.
Steel	8.12×10^{11}	20.9×10^{11}
Lead	0.56×10^{11}	1.62×10^{11}
Glass	$3. \times 10^{11}$	$7. \times 10^{11}$
India rubber	1.6×10^{7}	$5. \times 10^{9}$
Ice (*a*)	1.6×10^{6}	9.2×10^{6}
(*b*)		6.0×10^{6}
(*c*)	1.8×10^{6}	18.5×10^{6}

Thus we see that ice has much smaller elastic constants than metals and very small even compared to india rubber. For metals the value of Young's modulus is generally about three times as large as that of rigidity. For india rubber it is about three hundred times as great. For ice, the value of Young's modulus is from four to ten times as great as the rigidity, depending upon the orientation of the constituent crystals.

TORSION BY CONSTANT FORCE

As long as it remains within the limit of perfect elasticity, the deformation will little depend upon time. After that it will take considerable time before the final position of equilibrium is reached under a given force. For the purpose of finding the mode of yielding by constant force, a circular rod of ice with crystals transverse to it was twisted by different amount of torsional couple. The rod was 20.85 cm. long and 1.96 cm. in mean diameter. The torsional angle was observed at various times after a certain amount of weight was put on the hanging scale pan. The yielding curves under different weights are given in Figure 4.

As to the law of elastico-viscous flow of solids, Professor Michelson has published the results of his elaborate work with a formula which is to be used for materials of widely different properties.[2]

[1] C. W. C. Kaye and T. H. Laby, *Physical and Chemical Constants*, p. 27.

[2] A. A. Michelson, *Jour. Geol.*, Vol. XXV (1917), pp. 405–10, and Vol. XXVIII (1920), pp. 18–24.

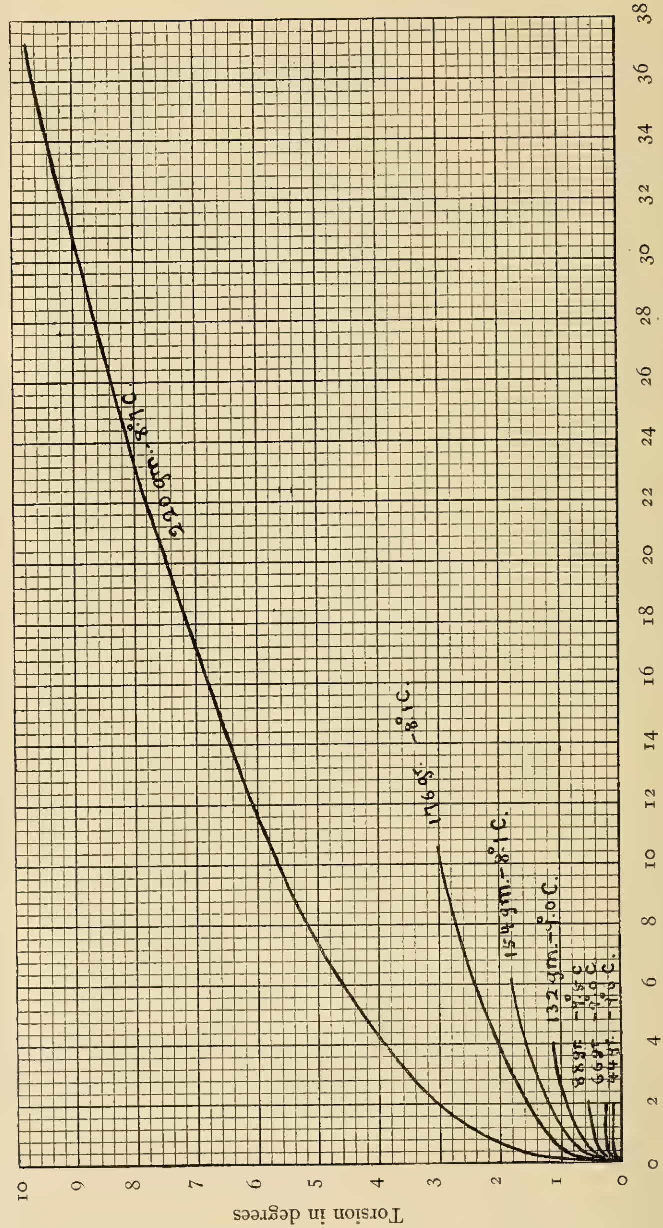

FIG. 4.—Torsion curves, by constant forces, of a circular ice bar, 20.85 cm. long and 1.96 cm. in diameter with crystals transverse to its longer dimension.

If we calculate the values of constants for that formula from the foregoing data, we can obtain the final value of torsion for each weight. Since the writer expects to obtain more detailed data for ice by further experiments, he will be, for the present, satisfied by finding the final positions by graphical extrapolation. The relation between the torsion and the applied force, thus found, is given in Figure 5. This curve is not the same as the curve in Figure 1, where the mode of application of force was different from the present case, as were also the dimensions of the test piece.

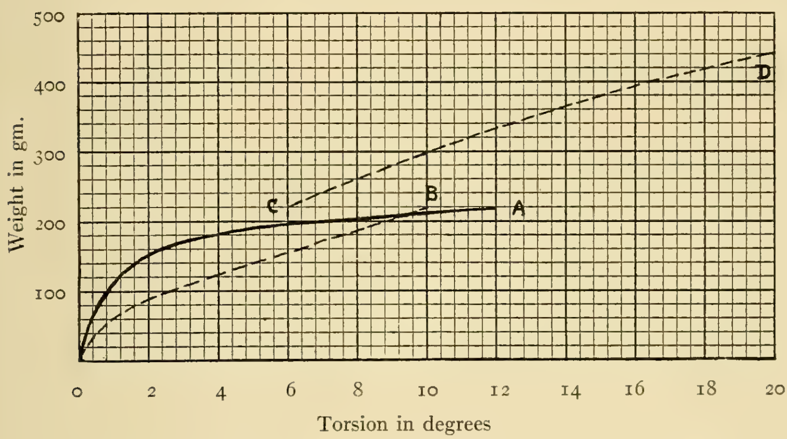

FIG. 5.—Torsion curves obtained from Figures 4 and 6. Full line: for the bar with crystals transverse to its longer dimension. Broken line: for the bar with crystals parallel to its axis.

Similar observations were tried on a test piece with crystals parallel to the length. It was 20.95 cm. long and 1.93 cm. in diameter (Fig. 6). During this test, it was noticed that the twisting curve for 308 gm. was very close to that for 220 gm. When repeated with 220 gm. once more, the deviation curve was found to be much lower than the former curve for the same amount of force. This fact suggests that ice shows the phenomena of elastic fatigue.[1] It was not learned whether this occurred after repetition of small deformations or after deformation of certain amount. It seems likely that this phenomena appears rather abruptly instead of gradually.

[1] Poynting and Thomson, *Properties of Matter*, p. 57.

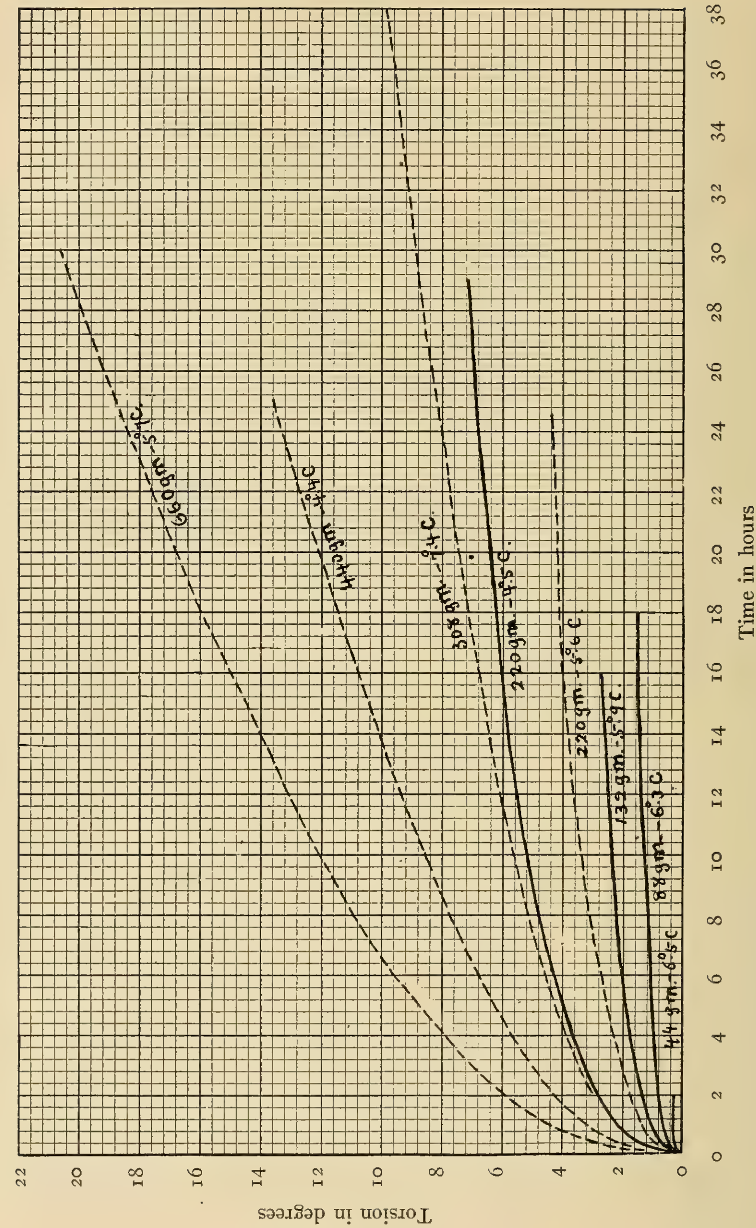

FIG. 6.—Torsion curves, by constant forces, of a circular ice bar, 20.95 cm. long and 1.93 cm. in diameter with crystals parallel to its axis.

The torsion curve for the case with crystals parallel to the axis of the test piece was also obtained as on the other case and is shown in Figure 5 by the broken line. Since the test specimens for these two cases were of nearly the same dimensions, we can compare the two curves with each other and consider the relative ease of yielding to torsional stress. As long as the deforming force remains less than 200 gm. the deformation for the former case is much smaller than for the latter. After that the curve becomes very flat showing that the specimen begins to yield readily. The curve for the latter rod shows a discrepancy between the points *B* and *C*. After that it still keeps on its steepness, becoming flatter after the point *D*, though this is not shown in the figure. Attention must be called to the fact that the observations for the former rod were made after it had been used repeatedly for other tests. It is, therefore, probable that this rod was already affected by the elastic fatigue when the present series of observations began. Lacking the knowledge how far this is the case, it is not safe to compare the curves for weights of less than 200 gm. When the weight is greater than this, it seems quite probable that the former rod, in which the constituent crystals are lying transverse to it, is twisted more easily than the latter, in which they are parallel to the length of the rod.

TORSION BY INCREASING FORCE

Whatever may be the fundamental property of ice by which the glacial motion takes place, the rate of accumulation of snow must be one of the most important factors influencing that motion. The corresponding study in the laboratory should be to find the relation between the deformation and different rates of increase of deforming force. For this purpose, a series of observations has been made with the same two test rods of different orientations of crystals as before.

The observed deformations of the first rod, where the crystals were arranged transverse to the rod, are shown in Figure 7. Since the deformation of a plastic body under constant force increases with time, it is clear that when the force increases slowly, the deformation for the same amount of force will be greater than when the force is increased rapidly. This relation is clearly shown in the

figure, the curve being steeper when the force is increased more rapidly. One curve, when the force was increased by the rate of 1.76 gm. per minute, is exceptional and steeper than the curves for the rates of 4.4 gm. and 2.2 gm. per minute as is shown by the broken line. The other curve for the same rate, which is not given in the figure, was very close to and slightly steeper than the curve for the rate of 2.2 gm. per minute. Since these two curves

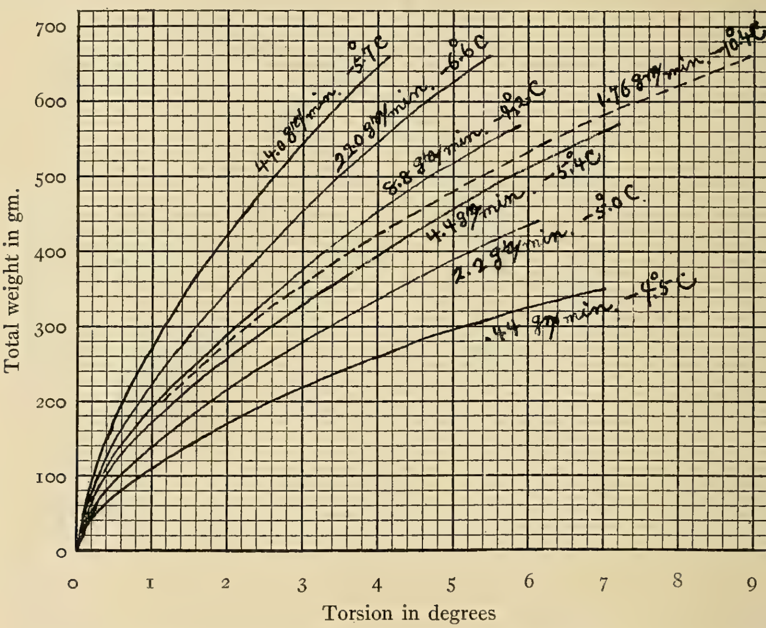

FIG. 7.—Torsion curves, by increasing force, of the first bar used for torsion by constant force.

were obtained by the last observations of the present series, the foregoing fact may be considered as the result of elastic fatigue. The difference between these two curves for the same rate of increase of force may be due to the difference of temperature which was respectively $-10^\circ.4$ C. for the steeper and $-4^\circ.6$ C. for the flatter.

Similar curves, though less numerous, were obtained with the second rod, in which the crystals were parallel to the length of the rod. These are shown in Figure 8. Here the deformation for

the rate of 1.76 gm. per minute was observed before it was used for the series of experiments on torsion by constant force in which the effect of elastic fatigue, as previously stated, was observed in pronounced form. The other two curves were obtained after that, and hence it is possible that the flatness of the first curve compared to the curve for .88 gm. per minute, which should not be the case, may be due to fatigue.

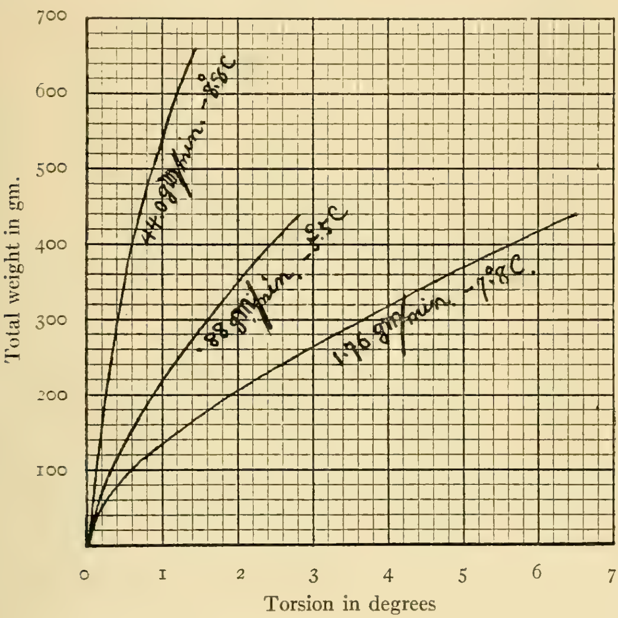

FIG. 8.—Torsion curves, by increasing force, of the second bar used for torsion by constant force.

The curves in Figure 7 were obtained after the observations for the torsion by constant force. We have seen before that the test piece was already subjected to fatigue in that case, and consequently the present curves will be affected in the same way. As a very rough approximation, therefore, we may compare the curves for the rates of .88 gm. and 44.0 gm. per minute in Figure 8, assuming the effect of fatigue to be the same after it has abruptly appeared and also neglecting the effect of temperature, which did not differ very much. The former curves are so much steeper that this

approximation seems safe. This steepness of the former curves means that ice is more easily twisted when the constituent crystals are arranged transverse to the rod than when they are parallel to its axis.

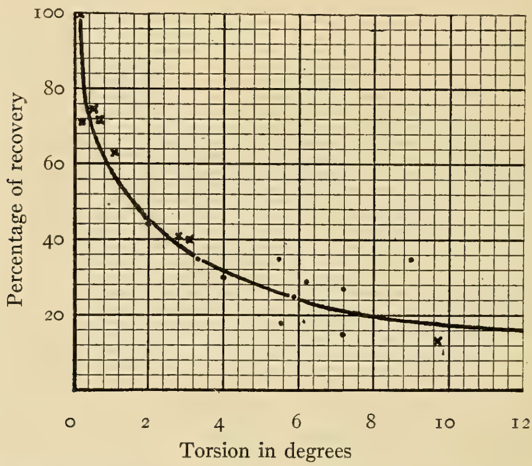

FIG. 9.—Recovery curve for the rod with crystals transverse to its longer dimension. Crosses for constant force and dots for increasing force.

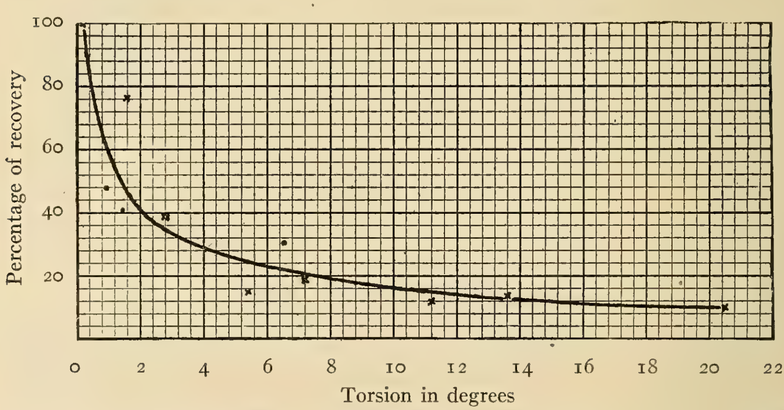

FIG. 10.—Recovery curve for the rod with crystals parallel to its axis. Crosses for constant force and dots for increasing force.

RECOVERY FROM DEFORMATION

While observing the deformations by constant force as well as by increasing force, the amount of return toward the original state

after removal of the force was observed in each case. Beside the amount of torsion, the recovery will depend upon various other conditions, like the temperature, mode of applying the force, and its duration. These values are given in the following tables:

Constant Force. Crystals Transverse

Temperature	Weight	Duration	Deformation	Recovery	Percentage
−9°.0C........	22 gm.	0^h15^m	0° 4′	0° 4′	100
−9.6.........	44	1 0	0 8	0 8	100
−9.0.........	66	1 0	0 14	0 14	71
−9.5.........	88	2 0	0 32	0 24	75
−9.0.........	110	3 5	0 36	0 26	72
−9.0.........	132	3 45	1 5	0 41	63
−8.8.........	154	6 20	2 50	1 2	41
−8.1.........	176	10 39	3 2	1 12	40
−8.7.........	229	37 20	9 44	1 18	13

Constant Force. Crystals Parallel

Temperature	Weight	Duration	Deformation	Recovery	Percentage
−9°.2C........	5 gm.	0^h55^m	0° 44′	0° 4′	100
−8.6.........	44	1 45	0 10	0 10	100
−6.3.........	88	15 10	1 38	1 15	77
−5.8.........	132	15 0	2 48	1 6	39
−7.3.........	229	29 30	7 12	1 21	19
−5.7.........	220	12 40	5 24	0 48	15
−7.1.........	308	48 0	11 11	1 16	12
−4.4.........	440	13 0	13 38	1 56	14
−5.7.........	660	18 0	20 36	2 8	10

Increasing Force. Crystals Transverse

Temperature	Increased Rate	Duration	Final Weight	Deformation	Recovery	Percentage
− 4°.5C......	.44 gm./min.	13^h20^m	352 gm.	7° 12′	1° 24′	19
− 4.7......	.88	5 0	264	3 20	1 10	35
− 4.6......	1.76	2 5	222	2 2	0 54	44
−10.4......	1.76	6 15	660	8 58	2 46	31
− 5.0......	2.2	3 20	440	6 8	1 46	29
− 5.4......	4.4	2 10	572	7 12	1 58	27
− 6.3......	8.8	1 5	572	5 28	1 42	31
− 4.3......	8.8	1 5	572	5 56	1 30	25
− 6.0......	22.0	0 30	660	5 30	0 58	18
− 5.7......	44.0	0 15	660	4 0	1 12	30

Increasing Force. Crystals Parallel

Temperature	Increased Rate	Duration	Final Weight	Deformation	Recovery	Percentage
− 7°.8C......	.88 gm./min.	3^h35^m	189 gm.	0° 57′	0° 25′	44
− 5.5......	1.76	4 10	440	6 30	2 0	31
− 9.0......	44.0	0 15	660	1 27	0 36	41

The amount of recovery in percentage of the deformation is shown in Figures 9 and 10. For small forces the recovery is complete. As the amount of force which has been used increases the percentage of recovery decreases rapidly until the formation amounts to about four degrees. After this its decrease becomes slower and it approaches gradually to the zero line. Thus it is seen that the transition from the stage of nearly perfect elasticity to that of partial elasticity takes place very slowly in the cases both when the torsion is parallel to the optic axis of the constituent crystals and when it is parallel to the basal planes.

BENDING EXPERIMENTS

The observations on torsion of ice just presented have suggested that an aggregate of parallel crystals of ice is more easily deformed by a shearing force parallel to the axes of the constituent crystals than parallel to their basal sections. We have also seen that Young's modulus, or proportionate resistance to elongation which is generally determined by the method of bending, is greatest when the deforming force bending the test bar acts parallel to the basal sections of the constituent parallel crystals. The next step was to test the matter further by observing the behavior of bars of differently orientated crystals when bent beyond the limit of elasticity. It was desirable to try the experiment with bars of different sizes compared to the constituent crystals. But the temperature of laboratory was not favorable for the use of larger bars with larger deforming force. Bars of moderate size with rectangular cross-sections were therefore prepared with different orientations of crystals. Each bar was supported at both ends by knife-edges and a weight of 100 gm. was hung from the middle point. The bending was measured by the lowering of this central portion. In Figure 11 some of the results of these observations are given, the data for the bars being given in the following table:

Bar	Optic Axes	Span	Breadth	Thickness	Temperature
a........	Horizontal	9.0 cm.	.90 cm.	.60 cm.	−5°8 C. to −2°0 C.
c........	Parallel	9.0	.90	.60	−5.8 to −3.0
b........	Vertical	9.0	.60	.58	−2.6 to −0.2
c........	Parallel	9.0	.60	.58	−2.6 to 0.0

The first specimen bent much more easily than the second and broke at the point *A* in the figure. The same applies to the third and fourth specimens.

In another case, three test pieces, each 0.80 cm. wide and 0.50 cm. thick, were supported with an 8.0 cm. span between the supports. The lowering of the central part by 100 gm. in the first eight hours was 2.68 cm., 0.2 cm., and 1.22 cm. respectively for the different orientations *a*, *b*, and *c*. A part of the weight

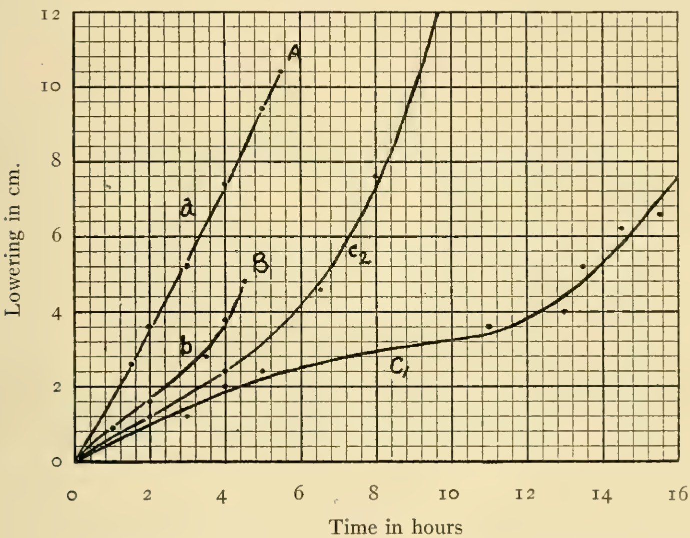

FIG. 11.—Relative ease of bending of ice bars with different orientations of crystals.

hanging from the second bar was found supported from beneath by accident so that its bending is not comparable with others. The temperature during this observation ranged from $-5^\circ.0$ to $-2^\circ.7$ C.

It is clear from these observations that ice bars with their constituent crystals perpendicular to the length, bend and break more easily than the bar with crystals parallel to the length. In the case of observation for the bars *b* and *c*, the temperature became so high that the bar suffered from pressure melting at the

knife-edges, thus preventing free movement. On account of this, the result may not be much relied upon and consequently the relative ease of bending of the bars *a* and *b* is not determined. The other observation stated above also failed to give any idea about this.

As to the nature of deformation of ice comprising of an aggregate of crystals, many authors have claimed that it depends upon the behavior of a single crystal. It is stated that in a case of bending of an ice bar consisting of several crystals, most of the bending had taken place in one of the crystals lying with its crystal axis nearly horizontal and approximately parallel to the length of the bar.[1] This is understood to mean that in such a case movement along the gliding planes of an ice crystal parallel to its basal plane is more effective than movements along the contact surfaces of adjacent crystals. If this theory is applicable to the present case the third bar in which the gliding planes were transverse to the long dimension should bend most easily. But quite to the contrary, bar of orientation *c*, instead of bending most readily, suffered the least bending of any of the three types of orientation.

As to the mechanism of bending within the limit of perfect elasticity it is generally understood by physicists that bending of a bar is caused by shortening of the concave side and elongation of the convex. When bending becomes larger than this, it is difficult to solve the case as a simple mechanical problem. It is probable in such a case that the portion near the point of application of force is subjected to bending, while the other parts are elongated with some degree of sliding at the knife-edges. The mechanism at the bending-point will depend upon the structure of the material. If it is deformable more easily in one direction than in another the problem becomes complicated. The resulting deformation in such a case will be the combination of that effect with the result of shortening and elongation phenomena. The experimental fact above described that bars of type *c* bend less easily than the others suggests that contact surfaces between adjacent crystals play greater rôle than the so-called gliding planes parallel to the basal plane.

[1] R. S. Tarr and J. L. Rich, *Zeits. f. Glets.*, Vol. VI (1911), p. 236.

MICROSCOPIC EVIDENCES

The theory that an ice crystal is composed of thin laminae parallel to its basal plane gives rise to the conclusion that when the crystal is bent by force perpendicular to its optic axis, it will show simultaneous extinction at the bent and unbent portions under the petrographic microscope.[1] Tarr and Rich[2] have described the case in which this optical property of the bent bar was not changed, as well as when it was changed. In the latter case the original optic axis was either parallel or perpendicular to the length of the bar, and if we assume the latter as the case, it is in contradiction to the idea that movement along the gliding planes controlled the bending.

The present writer examined the bent parts of an ice bar and the results were very suggestive, showing facts which seem not to agree with former ideas. A bar of ice with crystals parallel to its length was bent under certain stress. When the bent portion was thinned down and examined under the microscope with the Nicols crossed, it clearly showed an extinction strip across the bar, which moved along the bent portion as the stage was turned. Wanting to be sure about this, the writer asked Professor R. T. Chamberlin to see it and he recognized the same fact with certainty. The test piece in this case consisted of one main crystal with small portions of other crystals on either side. The same fact was observed in one more case but with the oncoming of warm weather these two were the only trials which it was possible to undertake in the present investigation.

Examinations without crossed Nicols revealed another important fact. The test specimen consisted of parallel crystals whose optical axes were horizontally transverse to the length. The bent portion was examined under microscope so as to see the side of the bar, i.e., the basal planes of the crystals. In the field of the microscope, it was found that faint but distinct straight lines nearly parallel to each other had developed on the sections of the crystals. The boundaries of the crystals were zigzag and sometimes the straight lines developed in the crystals were observed to

[1] R. S. Tarr and O. D. von Engeln, *Zeits. f. Glets.*, Vol. IX (1915), p. 111.

[2] R. S. Tarr and J. L. Rich, *Zeits. f. Glets.*, Vol. VI (1911–12), p. 235.

start from the angular points of these zigzag boundaries. The direction of the parallel straight lines was not the same in different crystals. Sometimes apparently two systems of these straight lines developed in one crystal, nearly perpendicular to each other. When the unbent portion of the same bar was examined in the same way, the crystals were found to be bounded by very smooth boundaries and no straight lines in their sections were visible. In another case, the same crystals were identified before and after bending took place. The same contrast of the disturbed and undisturbed crystals was observable in this case.

At the time of these observations, the equipment for petrographic photography was not available for the writer. He was obliged to content himself with very careful sketches of these phenomena as they appeared to him. These are shown in Figures 12 and 13. Since these figures represent the sections nearly parallel to the base, the straight lines in the sections must be considered to show the development of a system or two of parallel planes parallel to the optic axis. Uniform extinction was generally observed throughout each individual crystal, but in some crystals portions divided by the straight lines showed slight difference in extinction.

Bearing upon the question of straight lines in the section, Tarr and Rich[1] describe one case in which phenomenon of the sort were observed. They regarded it as notable, however, that this was the only one of their experiments in which bending took place by shearing. Their experiment was about the bending of a single crystal of glacier ice whose optic axis was parallel to the supporting edge. In the present investigation, the same phenomena was observed whenever the constituent crystals were perpendicular to the bending plane. It has already been stated that deformation either by torsional, or by bending, stress took place least easily when the force was applied parallel to the basal section of the constituent crystals. This was thought to suggest that in the deformation of an aggregate of parallel crystals, the contact surfaces between adjacent crystals probably have played an important

[1] R. S. Tarr and J. L. Rich, *Zeits. f. Glets.*, Vol. VI (1911–12), p. 243.

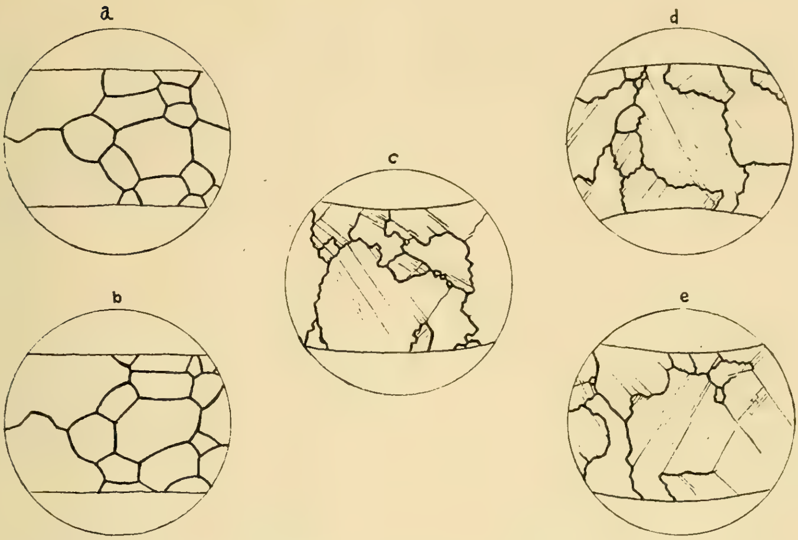

FIG. 12.—Microscopic appearances of ice crystals after bending. *a* and *b:* unbent portions. *c*, *d*, and *e:* bent portions.

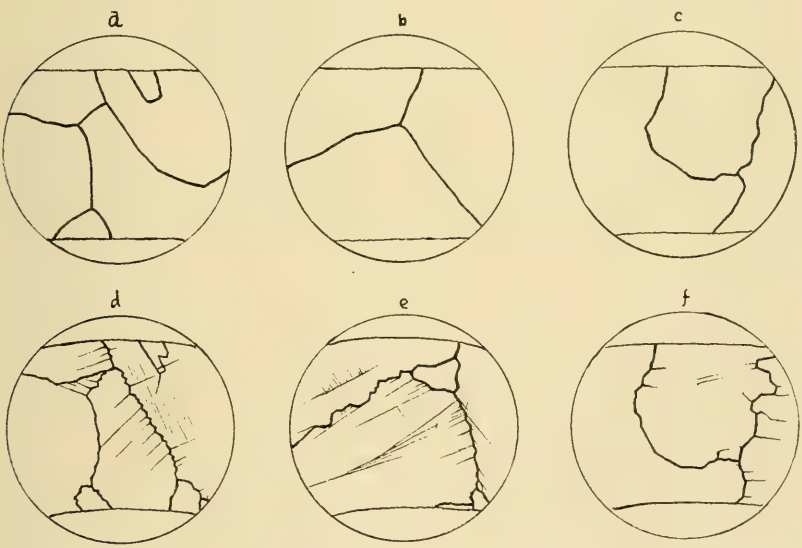

FIG. 13.—Microscopic appearances of ice crystals before and after bending. *a*, *b*, and *c:* before bending. *d*, *e*, and *f:* after bending.

part if the idea of McConnell and Mügge is correct. The development of the planes parallel to the optic axis suggests that an ice crystal has a greater tendency toward deformation parallel to the optic axis than perpendicular to it. To what degree this property of an ice crystal and the contact surfaces are concerned in the deformation of ice is to be decided by further study.

CONCLUSIONS

In some specimens of ice a sharply defined elastic limit was noted, though in other cases it was not so clearly shown.

The modulus of rigidity of ice, when the crystals are perpendicular to the axis of the test piece, is very small compared to that of metals, and is about 2×10^6 c.g.s. There is a slight indication that it is greater when the shearing is parallel to the base of the constituent crystals than when it is perpendicular.

The Young's modulus is also very small compared to that of metals. It is largest when the crystals are parallel to the length of the test piece, and has the numerical value about 20×10^6 c.g.s.

Elastic fatigue was marked after repeated torsion. On account of the fact that it was often necessary to use certain bars in successive experiments during which they suffered from different amounts of fatigue, it was difficult to compare the results bearing on ice bars with crystals parallel and perpendicular to the length of the test piece. Still there were some indications that beyond the limit of elasticity the former orientation was stronger than the latter against torsion. In the case of bending experiments, this was clearly shown.

The torsional deformations both by constant and by increasing forces were observed and the result is shown by curves, though no mathematical conclusions were made. The recovery curves showed that the observation was approaching the stage where no recovery would take place after removal of the force.

When an ice bar with crystals parallel to its length was bent, the bent portion showed the change of optical character, the extinction swinging around the curve. In each crystal when the bent specimen consisted of parallel crystals horizontally across it, parallel straight lines were observed.

These facts seem to show that gliding planes parallel to the base of each crystal are not the controlling factor in the deformation of ice and probably are not even an important factor. But instead, adjustments along the contact surfaces of adjacent crystals and perhaps the development of planes of weakness in the constituent crystals parallel to their long axis seem more effective in the process of deformation.

A TEST OF THE FELDSPAR METHOD FOR THE DETERMINATION OF THE ORIGIN OF METAMORPHIC ROCKS

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1. *Purpose of paper.*—That feldspars may serve as indicators of the original character of gneisses and schists is dependent upon the narrow range of composition possessed by the plagioclase feldspars of igneous rocks. Thus more than one kind of plagioclase feldspar is rarely found in an igneous rock except in certain zonal intergrowths or in some porphyries where the feldspars forming the phenocrysts may be of slightly different composition from those of the groundmass.

In sediments, except in rare cases where they are derived from rocks having feldspars with a narrow range of composition, the limited feldspar composition found in igneous rocks is not to be expected. Usually sediments are derived from many sources and consequently mixtures of all kinds of feldspars are possible. It would seem reasonable then to believe that gneisses and schists with a narrow range of feldspar composition are probably igneous in origin, whereas metamorphic rocks with several varieties of feldspar are very likely of sedimentary origin. This belief, however, rests on the fundamental assumption that the feldspar range typical of sediments does not radically change during anamorphism of these sediments. It is readily seen that if such a change does take place it vitiates any conclusions which might be reached. Similarly, if in the anamorphism of igneous rocks a radical change in the original feldspar composition results, this also would militate against the efficacy of the feldspar method.

That feldspars undergo alteration in various stages of the metamorphic cycle is generally recognized. It is not known that this

alteration tends to produce feldspars of varied composition from one particular feldspar, nor conversely to change a wide feldspar range into a narrow one.

The purpose of the work of this thesis was to determine the efficacy and validity of the hypothesis as above stated, namely, that metamorphic rocks having a narrow range of feldspar composition are probably igneous in origin, whereas those having a wide range of feldspar composition are more likely of sedimentary origin. To test the validity of this hypothesis it was first necessary to get some idea as to the abundance of feldspars in various sediments and also to determine the range in composition of these feldspars. This involved a study of sediments both in the unconsolidated and consolidated form. It was then further necessary to study metamorphic rocks of known sedimentary and igneous origin in order to note whether the feldspar composition was such as would have characterized the original sedimentary or igneous equivalent. The methods used in this study and the results obtained are presented in this paper.

The writer wishes to acknowledge his indebtedness to Dr. Edward Steidtmann, of the University of Wisconsin, for suggesting the fundamental idea upon which the feldspar method is based, and to Professors A. N. Winchell and C. K. Leith for suggestions and criticisms.

2. *Methods used to determine feldspars.*—In the determination of the feldspars two distinct methods were used depending upon the character of the material to be examined. Where thin sections were available and the rock was fairly coarse grained the Fouque method was found very serviceable.

When thin sections were not available and the material was so fine grained as not to be adapted to the Fouque method, the material was studied in powdered form and the feldspars determined by immersion in a series of liquids of known index. With the liquids either the Becke or inclined illumination method can be used. The determination of feldspars from rock powders in this manner is especially valuable in cases where the feldspars are partly altered, where the rock is fine grained, when the feldspar content is low, and for all unconsolidated sediments.

3. *The materials studied.*—In getting material together for study the attempt was made to make this selection one which would most thoroughly test the feldspar method. The mineralogic composition of unconsolidated and consolidated sediments as well as of metamorphic rocks of known origin was therefore determined. In order that the sediments might represent the breaking down of as many rock formations as possible, they were chosen so as to include a wide geographic and stratigraphic distribution. The aim was also to avoid limiting the material studied to any one particular realm of deposition. Beach sands as well as sands of glacial, eolion, and locustrine origin were therefore chosen. The consolidated sediments examined included arkoses, graywackes, tuffaceous sandstones, and shales. Since the purpose of studying the metamorphic rocks was to determine whether anamorphism causes any changes in the feldspar composition of the original rock, the gneiss and schists were selected which showed different kinds and degrees of change.

4. *Tabulation of results.*—The table on page 636 shows the results of the feldspar determinations for the various kinds of material studied.

5. *The relative abundance of feldspars in sediments.*—The data available are not sufficient to warrant a dogmatic statement as to whether certain feldspars are more abundant in sediments than others. The studies by the writer of a large number of sediments of different origin, as well as of wide geographic and stratigraphic distribution, suggest very strongly, however, that certain feldspars are very common in sediments, whereas others are quite rare. Orthoclase, microcline, and the acid plagioclases are much more frequently met with in sediments than the basic feldspars. Microcline seems to be more common than any of the others, so that a careful study of sands which appear to be entirely composed of quartz usually reveals a few grains of this feldspar. By referring to the accompanying diagram (Fig. 1) the relative abundance of the various plagioclase feldspars is strikingly brought out. This abundance of the feldspars mentioned indicates either that they are especially common in the rocks from which they were derived or that the basic plagioclases suffer much more rapid

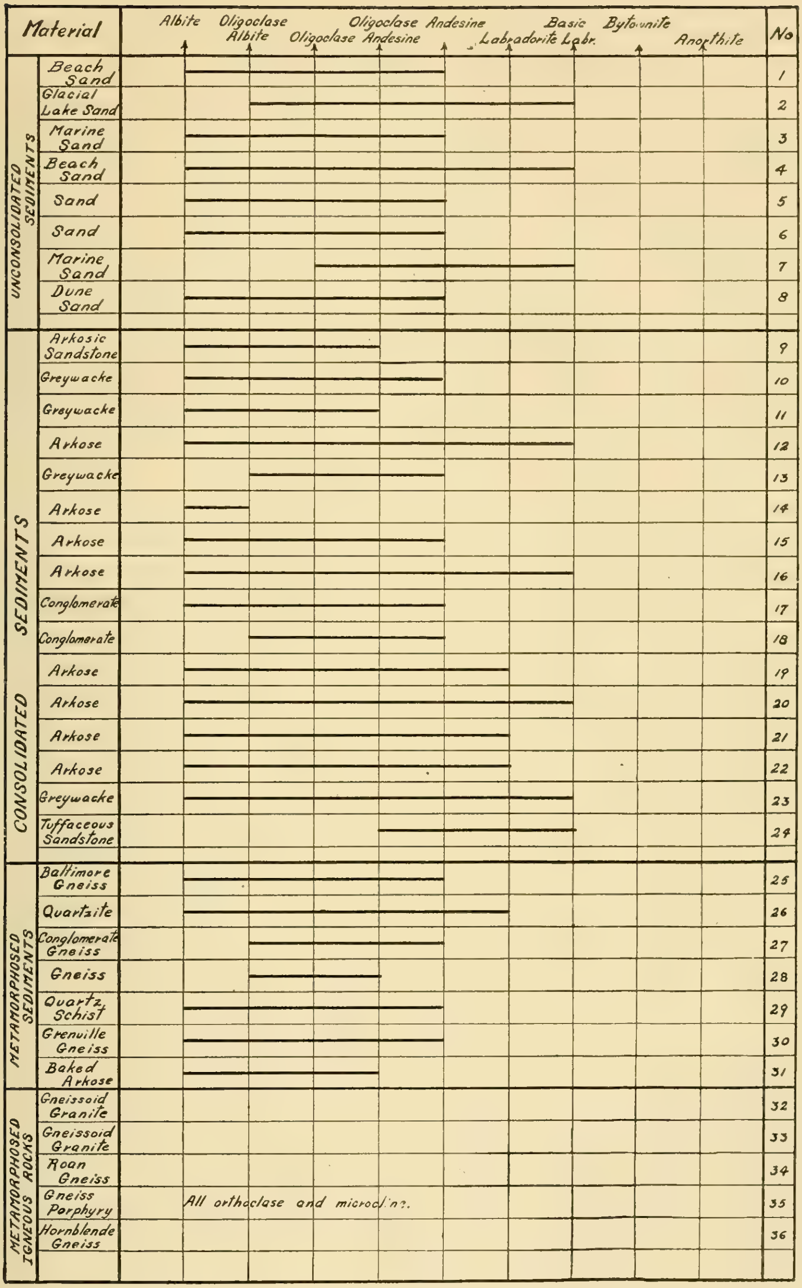

FIG. 1.—Diagram showing the range in feldspar composition for the various materials studied. The numbers refer to those on the accompanying tables where additional data are given. The solid black lines opposite the material indicated in the left-hand column show the range in feldspar composition for that material. Note the wide range of feldspars in the material of sedimentary origin as compared to that which is igneous in origin.

TABLE SHOWING DATA OBTAINED AS TO FELDSPAR COMPOSITION OF SEDIMENTS AND METAMORPHIC ROCKS OF KNOWN ORIGIN

	No.	Material	Locality	Feldspars Found	Method Used*	Remarks
Unconsolidated Sediments	1......	Quartz Beach sand	South Carolina, Sullivans Island	Albite oligoclase, andesine, microcline, and orthoclase	B	Feldspar forms about 5 per cent of sand
	2......	Glacial Lake sand	Middleton, Wisconsin	Oligoclase albite, oligoclase, andesine, labradorite, basic labradorite microcline	B	....
	3......	Marine sand Cambrian	South Point, Wisconsin	Albite, oligoclase, andesine, orthoclase, and microcline	B	Mineralogical composition of this sand=36 per cent carbonate, 45 per cent quartz, 14 per cent feldspar, 5 per cent augite, hypersthene, apatite, zircon, garnet
	4......	Beach sand. Largely derived from limestone but containing some glacial sand	Anticosti Island	Albite, oligoclase, andesine, basic labradorite, orthoclase, microcline	B	Mineralogical composition of this sand=85 per cent carbonate, 8 per cent shale particles, 7 per cent quartz, feldspar and heavy residuals
	5......	Sand. Contains reworked glacial material	From mouth of estuary between Goose and Lacroix Points, Anticosti Island	Albite, oligoclase, andesine, microcline, and orthoclase	B	Mineral composition—52 per cent c arbonate, 43 per cent quartz, and feldspar, 5 per cent heavy residuals. Bulk of sand of .124 mm. size
	6......	Sand. Largely derived from limestone	From work in Chicotte formation Anticosti Island	Albite, andesine, microcline	B	Mineral composition=powder. 94 per cent carbonate, 4 per cent quartz, and feldspar; 2 per cent rock and mineral particles, 83 per cent of material coarser than .417 mm.

Consolidated Sediments	7......	Marine sand Cambrian	Middleton, Wisconsin Interstratified with Oneota dolomite	Oligoclase, andesine, labradorite, basic labradorite, orthoclase and microcline	B	Mineral composition: 60 per cent quartz, 27.4 per cent carbonate, 11 per cent feldspar, 1.6 heavy residuals. Microcline abundant
	8......	Dune sand	Golden Gate Park, California	Albite, oligoclase, andesine, microcline and orthoclase	B	....
	9......	Arkosic sandstone	Wausau, Wisconsin	Albite, oligoclase, oligoclase andesine, orthoclase and microcline	F	Plagioclase feldspars abundant. Pre-Cambrian
	10......	Graywacke	Wausau, Wisconsin	Albite, oligoclase albite andesine, orthoclase	F	Pre-Cambrian
	11......	Graywacke	Wausau, Wisconsin	Albite, oligoclase, andesine oligoclase, orthoclase	F	Pre-Cambrian
	12......	Arkose Jurassic Triassic	New Jersey	Albite, oligoclase, albite, andesine, basic labradorite, microcline	B	Rock is from the Newark series; interpreted as being of terrestrial origin
	13......	Graywacke Huronian	Hurley, Wisconsin	Oligoclase albite, oligoclase, oligoclase andesine, orthoclase and microcline	F	Rock composed of quartz and feldspar chiefly. Rock particles also present
	14......	Arkose (Brown sandstone)	Hummelstown, Pennsylvania	Albite, oligoclase albite, orthoclase and microcline	F	Rock is part of Newark Series, of Jurassic-Triassicage
	15......	Arkose	Clinton Point, Wisconsin	Albite, oligoclase, albite, oligoclase andesine	F	Feldspar is considerably kaolinized

* The letters B and F under the column headed "Method Used" stand for Becke and Fouque.

TABLE SHOWING DATA OBTAINED AS TO FELDSPAR COMPOSITION OF SEDIMENTS AND METAMORPHIC ROCKS OF KNOWN ORIGIN—*continued*

	No.	Material	Locality	Feldspars Found	Method Used*	Remarks
Consolidated Sediments	16......	Arkose	Whitehall, Montana	Albite, oligoclase albite, oligoclase, andesine, basic labradorite, orthoclase	F	Plagioclase is abundant. Rock is fine-grained conglomerate
	17......	Conglomerate Huronian	Cobalt, Ontario	Albite, andesine, microcline and orthoclase	F	Plagioclase not abundant
	18......	Conglomerate	Oconto Bay, Wisconsin	Oligoclase albite, andesine, orthoclase and microcline	F	Plagioclase not abundant
	19......	Arkosic sandstone Keweenawan age	Ontonogan County, northern Michigan	Albite, andesine, labradorite, microcline and orthoclase	B	Labradorite least abundant of plagioclases
	20......	Arkose	Devils Rock, Cobalt District, Ontario	Albite, oligoclase, andesine, basic labradorite, orthoclase and microcline	B	Orthoclase abundant. Huronian
	21......	Mashed arkose	Portage, Minnesota	Albite, oligoclase, andesine, labradorite, orthoclase and microcline	B	Microcline abundant; some of feldspars partially recrystallized. Huronian
	22......	Arkosic sandstone	Southeast of Houghton, Michigan	Albite, andesine, labradorite, microcline	B	Cambrian
	23......	Graywacke	Grafton Center, New Hampshire	Albite, oligoclase, andesine, basic labradorite	B	....

Metamorphic Sedimentary Rocks	24......	Tuffaceous sandstone	Teslo, California	Oligoclase, andesine, labradorite	B	....
	25......	Baltimore gneiss	Baltimore, Maryland	Albite, andesine	B	....
	26......	Arkosic quartzite	Temiskaming, Ontario	Albite, andesine, labradorite, microcline, orthoclase	B	Huronian age
	27......	Conglomerate gneiss	Mill River, Massachusetts	Oligoclase, albite andesine, orthoclase, microcline	B	Microcline abundant
	28......	Gneiss	Tyringham, Massachusetts	Oligoclase albite, oligoclase andesine, microcline and orthoclase	F	Microcline abundant
	29......	Quartz schist	Ramshorn District, Montana	Albite, oligoclase, andessine, orthoclase	F	....
	30......	Grenville gneiss	Near New York City	Albite, oligoclase, andesine	B	....
	31......	Baked arkose conglomerate	South Britain Connecticut	Albite, oligoclase, andesine	B	....
Metamorphic Igneous Rocks	32......	Gneissoid granite	Three Rivers, Massachusetts	Albite only	B	....
	33......	Gneissoid granite	Thomaston, Connecticut	Albite only	B	....
	34......	Roan gneiss	Northern Georgia	All andesine	B	....
	35......	Gneiss porphyry	Dame de Muse, Ardenned, Belgium	All above albite. Microcline and orthoclase abundant	B	....
	36......	Hornblende gneiss	Ilchester, Maryland	All andesine	B	....

*The letters B and F under the column headed "Method Used" stand for Becke and Fouque.

decomposition. The latter seems the more reasonable conclusion since many of the sediments studied have had their origin in areas of basic igneous rocks. At Keweenaw Point for example the Keweenawan sediments show a very small amount of the basic feldspars as compared to the acid varieties and yet the sediments have been largely derived from rocks of a decidedly basic character and from rocks in which basic feldspars are known to be very common. It is also generally recognized that the calcic feldspars are more readily decomposed than the more alkaline varieties. Iddings states that

> The alkalcic feldspars are not attacked by hydrochloric acid. The more calcic feldspars are decomposed by the acid in proportion to their content of calcium. Thus oligoclase and andesine are not attacked, labradorite is slightly acted upon, bytownite and anorthite are decomposed with the separation of gelatinous silica. In the rocks the more calcic feldspars are more readily decomposed than the more alkalcic feldspars in general.[1]

Feldspars are much more common in sediments than has generally been supposed. A large number of "sandstones" and "quartz" sands were in many cases found to have a considerable percentage of feldspar. Sands with a 5 per cent content of feldspar are not at all uncommon, while certain glacial and marine beach sands may contain feldspar up to 25 per cent.

6. *Feldspar range of rocks studied.*—It was desired to determine, by the work pursued in connection with this thesis, just what range in feldspar composition can be expected in sediments, and further to ascertain whether, during anamorphism, there is any change in the feldspar composition of the original igneous or sedimentary equivalent. The results obtained show that almost any combination of the various feldspars can be found in sedimentary rocks. Of the twenty-four samples studied, these samples including unconsolidated and consolidated sediments, twenty-three showed a range in feldspar composition from albite to andesine. Labradorite was found in eleven of the samples, while anorthite, due undoubtedly largely to its ready solubility as well as comparative rarity was not noted in any of the samples studied. As was expected glacial and marine beach sands show a very large range

[1] J. P. Iddings, *Rock Minerals*, p. 204.

in feldspar composition. Studies of metamorphic rocks of known igneous and sedimentary origin showed that the former retained their limited feldspar composition, whereas the metamorphic-sedimentary rocks included feldspar combinations such as would characterize the original sedimentary rock. The conclusion, as based upon the work done, is that there is no decided change, during anamorphism, of the feldspar composition possessed by the original unmetamorphosed material.

7. *The usefulness of the feldspar method as compared with the present criteria used in the determination of the origin of metamorphic rocks.*—The present criteria which are used to determine the igneous or sedimentary origin of metamorphic rocks are dependent upon field relations, together with chemical and mineralogical composition. Field evidence consists chiefly in tracing metamorphic rocks into the less altered igneous or sedimentary equivalents. Thus a basalt has often been observed to grade into a chlorite or micaceous schist. Similarly banded gneisses are often associated with and grade into granites. Chemical evidence suggestive of a sedimentary origin consists, according to Bastin[1] "of a dominance of magnesia over lime, potash over soda, excess of alumina and high silica. If the chemical composition is essentially that of an igneous rock this fact favors igneous origin." Mineralogical evidence favoring a sedimentary origin consists of a high content of quartz as does also an abundant development of aluminum silicate minerals. The presence of graphite probably denotes a sedimentary rather than an igneous origin.[2] Rounded grains of such minerals as garnet, sphene, and especially zircon have been taken as evidence of sedimentary origin. These minerals are especially resistant to weathering and will remain after the other minerals have been completely altered.

The plagioclase feldspar method is an addition to our mineralogical criteria. The results obtained prove the feldspar method to be a valid and reliable method for the determination of the

[1] Edson S. Bastin, "Chemical Composition as a Criterion in Identifying Metamorphosed Sediments," *Jour. Geol.*, XVII (1909), p. 472.

[2] J. D. Trueman, "The Value of Certain Criteria for the Determination of the Origin of the Foliated Crystalline Rocks," *Jour. Geol.*, XX (1912), pp. 228–58, 300–15.

metamorphic rocks to which it is applicable, and this means any rock containing recognizable feldspar constituents. The studies show that metamorphic rocks in general, except where they have suffered alteration due to ordinary weathering or hydrothermal alteration, contain such constituents. Where hydrothermal alteration has been effective, as in the proximity of the intrusive porphyries of the west, some other criteria must generally be resorted to. Even here, however, the alteration is not likely to have proceeded far from the main intrusive, so that by following a formation into its unweathered portion, recognizable feldspars may often be found. The feldspar method is to be preferred to the heavy residual or "zircon" criterion. The theory upon which the heavy residual method is based is undoubtedly a valid one, yet the studies of a large number of sediments show that any interpretations as to the origin of metamorphic rocks which are based upon its use, cannot be but uncertain. In the examination of marine beach sands from South Carolina and Anticosti Island, crystals of zircon and titanite were found which retained perfectly their crystal outline. Dr. W. H. Twenhofel reports similar results from a study of coral beach sands from the Hawaiian Islands. Such a sediment after conversion to a metamorphic rock would, on the basis of the zircon method, have been interpreted as suggestive of igneous origin. It must be borne in mind, however, that of all the criteria at present available for the determination of the origin of schists and gneisses, the use of field relations, where possible, is by far the most conclusive. Chemical and mineralogical criteria must therefore be subordinated to it. On the basis of practical usefulness and reliability the feldspar criterion should supply a valuable addition to our present laboratory methods.

SUMMARIES OF PRE-CAMBRIAN LITERATURE OF NORTH AMERICA

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II. ONTARIO

In the region northeast of Lake Huron, the pre-Cambrian rocks according to Collins and others show one conspicuous unconformity. The rocks beneath this unconformity comprise a series of quartzites and other clastic sediments, the Timiskaming series, etc., intruded by granitic rocks. Unconformably beneath these sediments is an older series, the Keewatin, including basic flows, some acid extrusives, iron formations, dolomites, etc. The Keewatin is intruded by the Laurentian granites and gneisses.

Above the conspicuous unconformity are two series of slightly metamorphosed dominantly clastic sediments separated by an inconspicuous unconformity. The lower one, the Bruce series, locally contains tillites. The upper series is generally known as the Cobalt series. At Killarney on the north shore of Lake Huron, Collins has found that the Bruce and possibly the Cobalt series are intruded by the Killarney granite and in this locality they assume many of the characteristics of the older series, the Timiskaming. The youngest pre-Cambrian rocks are Keweenawan, basic dikes and sills.

Northwest of Lake Superior, Lawson has restudied the Rainy Lake and Steeprock Lake districts. Greenstones and other rocks typical of the Keewatin are widely exposed in this region. Beneath them are acid schists called Coutchiching by Lawson. Unconformably above the Keewatin in the vicinity of Rainy Lake are a series of conglomerates and slates called the Seine series by Lawson. In the Steeprock Lake district, the Steeprock Lake series lies unconformably between the Keewatin and Seine series. The Steeprock Lake series, besides clastic sediments, comprises fossil-bearing dolomites.

The youngest rocks of the region are basic dikes classed as Keweenawan.

Baker[1] classifies the pre-Cambrian rocks of the Kingston area in southeastern Ontario as follows:

Great unconformity
Keweenawan—Trap, diabase, and gabbro intrusives
Intrusive contact
Algoman—Coarse-grained granite and syenite intrusives with later pegmatites
Intrusive contact
Laurentian—Gray to pink, medium to fine-grained, granitic gneisses
Intrusive contact
Grenville—White, coarsely crystalline limestone with quartzite and rusty weathering gneisses.
Dark green to black gneisses—thoroughly impregnated with minute dikes of Laurentian granite, now also changed to gneiss.

As reported by E. L. Bruce,[2] the succession in the Cripple Creek Gold district located about twenty-five miles southwest of Porcupine, Ontario, is:

Glacial and Recent
Peat, unsorted and more or less sorted sands and clays
Unconformity
Post-Laurentian
Diabase dikes
Igneous contact
Laurentian
Gray granite—reddish gneissoid granite
Igneous contact
Keewatin
Greenstones, schists, diabase, and iron formation

The Kirkland Lake and Swastika[3] gold areas are located in the Timiskaming district, fifty miles north of Cobalt. The pre-Cambrian rocks are classified as follows:

Later dikes—Diabase
Intrusive contact

[1] M. B. Baker, "The Geology of Kingston (Ontario) and Vicinity," *Ontario Bur. Mines, 25th Ann. Rept.*, Vol. XXV, Part 3 (1916), pp. 1–36, 19 figs., map.

[2] E. L. Bruce, geologist, and W. R. Rogers, topographer, "Cripple Creek Gold Area, *Ontario Bur. Mines*, Vol. XXI (1912), Part I, pp. 256–65, 9 figs.

[3] A. G. Burrows and P. E. Hopkins, "The Kirkland Lake and Swastika Gold Areas, *Ontario Bur. Mines, 23d Ann. Rept.*, Vol. XXIII, Part II (1914), pp. 1–39.

Cobalt series—Nearly flat-lying conglomerate with bowlders of granite and syenite
Unconformity
Post Timiskaming intrusives—Granite, syenite, feldspar, porphyry, lamprophyre
Intrusive contact
Timiskaming series—Quartzite, graywacke, conglomerate with schistose derivatives. The conglomerates contain a variety of pebbles derived from the Keewatin
Keewatin—Greenstone (basalt andesite) diabase, quartz porphyry, feldspar porphyry, iron formation, dolomite

Burrows[1] maps the Matachewan Gold area on Montreal River in latitude 48. Below is the table of formations:

Animikean-Cobalt series—Conglomerate, quartzite, graywacke, slate
Unconformity
Algoman—Granite, syenite, and thin acid intrusives
Intrusive contact
Laurentian—Granite and gneiss
Keewatin—Greenstones, iron formation, some quartzite, conglomerate, etc.

Burrows[2] classifies the pre-Cambrian rocks of the Porcupine Gold area of Ontario as follows:

Keweenawan—Quartz diabase, olivine diabase
Intrusive contact
Algoman—Granite porphyry, feldspar porphyry
Intrusive contact
Pre-Algoman—Lamprophyre, serpentine quartz porphyry
Intrusive contact
Timiskaming series—A series of schistose conglomerates, interbanded slate and graywacke, quartzite "carbonate" rock
Unconformity
Keewatin—A couple of largely schistose basic to acid volcanics, agglomerates, ash rocks, iron formation, rusty weathering, "carbonate," diabase, serpentine, etc.

The gold occurs in quartz veins cutting the Keewatin and Timiskaming series and the pre-Keweenawan intrusives. They are believed to be related genetically to the Algoman intrusives.

[1] A. G. Burrows, "The Matachewan Gold Area," *Ontario Bur. Mines, Ann. Rept.*, Vol. XXVII (1918), Part I, pp. 215–40, maps and illustrations.

[2] A. G. Burrows and P. E. Hopkins, "The Porcupine Gold Area" (Third Report), *Ontario Bur. Mines, Ann. Rept.*, Vol. XXIV, Part III (1915), pp. 1–57, 44 figs. inclusive, maps; see also *ibid.* (Second Report), *Ontario Bur. Mines 21st Ann. Rept.*, Vol. XXI (1912), pp. 205–49, 37 figs.

The Whiskey Lake[1] area includes two unsubdivided townships, Nos. 137 and 138, in the third and fourth tier of townships north of Lake Huron. The pre-Cambrian rocks of the area are provisionally classified as:

Middle Huronian—Conglomerate and quartzite
  Unconformity
Lower Huronian—Conglomerate, quartzite, slate, and limestone
  Great unconformity
Sudbury series—Slate and probably quartzite, part of the greenstone
  Unconformity
Keewatin—Most of the greenstone and green schist
Laurentian—Granite and syenite

Coleman[2] classifies the pre-Cambrian succession along the north shore of Lake Huron as follows:

Keweenawan—Basic volcanic eruptives and basic sills. Subordinate coarse, usually red sediments, probably indicating warm, dry climate
Animikie—Black slates, volcanic tuff, bowlder conglomerate
Huronian—Arkose and quartzite, shallow lake or sea deposits indicating cool climate. Bowlder conglomerate or tillite formed under glacial conditions
Sudburian—Pillow basic lava flows. Coarse sediments—conglomerates, bowlder beds, arkoses, quartzites derived mainly from the disintegration of granites
Grenville—Quartzites, schist, and impure calcareous sediments whose relation to the Keewatin is uncertain. Intrusion of granites
Keewatin—Basic eruptions and jaspititic iron formations

Coleman[3] classifies the pre-Cambrian rocks of the region north of Lake Huron extending from Point Mamainse to Wanapitie as follows:

Post-Laurentian	Keweenawan
	Discordance
	Animikie
	Discordance
	Upper Huronian
	Great discordance
Pre-Laurentian	Sudbury series
	Great discordance
	Keewatin—Probably equal to the Grenville series

[1] A. P. Coleman, "The Whiskey Lake Area," *Ontario Bur. Mines, 22d Ann. Rept.*, Vol. XXII (1913), Part I, pp. 146–54, 5 figs.

[2] A. P. Coleman, "The Pre-Cambrian Rocks North of Lake Huron with Special Reference to the Sudbury Series," *Ontario Bur. Mines, Ann. Rept.*, Vol. XXIII (1914), Part I, pp. 204–36, map, 18 figs.

[3] A. P. Coleman, "The Sudbury Series and Its Bearing on Pre-Cambrian Classification," *Congrès Géologique International XII.* Session 1914.

The major divisions are based on the position of the various series with reference to a conspicuous unconformity and to certain granite batholiths. He recommends that this section be adopted as a standard for the Lake Superior region.

In 1915 Coleman[1] classified the rocks of the Canadian Shield to the northeast of Lake Huron as follows:

Late Proterozoic	Keweenawan (Mamainse and nickel eruptive)	
	Discordance	
	Upper Huronian	Typical Huronian
	Small discordance	
	Lower Huronian	
	Great discordance	
Early Proterozoic	(Laurentian granite and gneiss)	
	Eruptive contact	
	Sudburian—Timiskaming, Pontiac, etc.	
	Great discordance	
Archaeozoic	(Granite eruptive through lower series)	
	Eruptive contact	
	Keewatin and Grenville	

The important points of this classification are the recognition of two major unconformities in the succession and the naming of certain granites and gneisses which are intrusive into rocks younger than the Keewatin, as Laurentian. In his discussion following the classification, he substitutes the term Animikie for Upper Huronian. The term Sudburian for a series is recent in the general discussions of the stratigraphy of the Canadian Shield. This series, Coleman states, is typically developed in the Sudbury district, where it consists chiefly of quartzites, slates, and conglomerates, without limestones or dolomites, and with almost no carbon. These rocks are severely folded, but not intensely altered excepting near intrusives. Their deposition was followed by the extrusion of lava Sudburite, the effusive equivalent of Norite. Other probably Sudburian areas include portions of the region to the northeast of the Wahnapitae River, and the Timiskaming, Gowganda, Larder Lake districts, the area of the Pontiac series of Quebec, the Doré formation of the east shore of Lake Superior, and certain rocks of Heron Bay on the north shore of Lake Superior,

[1] A. P. Coleman, "The Proterozoic of the Canadian Shield and Its Problems," *Problems of American Geology* (1915), pp. 81–161.

the Nipigon area, the Onaman Iron Range, and the Seine River in the Rainy Lake district. The Sudbury series he regards as being partly a delta deposit laid down in a moist cool climate, but finds it strange that carbon is lacking. In the interval between Sudburian and Huronian time, the area was folded and eroded to a surface very much like that of the present Canadian Shield.

For the nature of the Lower Huronian, he refers to Logan's type section on the northeast coast of Lake Huron. Tillites are a characteristic constituent of the Huronian, but in addition it contains stratified deposits. Other Lower Huronian areas are found in the Larder Lake, Chibougama, and Steep Rock Lake districts. The Lower Huronian rocks have a marked unconformity at their base, but are in general less severely folded than the Sudbury series. At the start the climate of the period appears to have been cool and glacial. The existence of animals is suggested by the occurrence of limestone.

The Animikie he characterizes as a period of great submergence during which great quantities of iron compounds and black slates were deposited.

The Keweenawan of the Canadian Shield rests upon the eroded Animikie. It includes three series, of which the two lower are chiefly sedimentary, while the upper is largely volcanic. The sediments consist largely of sandstones and conglomerates, characterized by red color and absence of carbon. The volcanics are chiefly basic flows, but possibly include some felsites and porphyries. Dikes are common, but as yet no definite volcanic vents have been found. Other areas of the Canadian Shield probably containing Keweenawan are the Nastapoka and Manitaunick Islands, Central Labrador, and the south side of Hudson Straits, the regions of Lake Athabasca, Great Slave Lake, and the area between the east side of Great Bear Lake along the Copper Mine River northward to the Arctic Ocean. Deposition during Keweenawan time, according to Coleman, was chiefly on the land in a warm dry climate. He speculates as to the source of great quantities of lavas and relates the development of the Lake Nipigon, Sudbury, and Lake Superior basins to the collapse of the surface resulting from the extrusion of the lavas.

The base of the succession exposed in the Gowganda[1] district consists of Keewatin greenstones mostly of igneous origin associated with some iron formation. They are intruded by batholiths of Laurentian granite. Overlying the granites and greenstones with well-marked unconformity are Huronian sediments which are separated into two members by a faint unconformity. The lower group from 500 to 1,000 feet thick consists of conglomerates, arkose, graywacke, and slates, showing poor assortment, variable bedding, and till-like character in the coarse phases. Locally, the beds are associated with rhyolitic extrusions. The upper is a single quartzite formation 600 or more feet thick, ranging from arkose to pure, well-bedded quartzite.

Intruded into the preceding are Keweenawan diabase sills and dikes.

Selected areas between the original Huronian and the Cobalt and Sudbury districts were examined by Collins[2] with the view of correlation. The Bruce, Blind River, Whiskey Lake, Española, and Round Lake areas were selected, the widest gap between them being about 28 miles.

Collins recognizes two major stratigraphic divisions, the pre-Huronian and the Huronian. They are separated by the most conspicuous unconformity of the region, characterized by a strong basal conglomerate, great differences in structure, metamorphism, igneous intrusions, and general lithologic character of the two groups. The pre-Huronian consists of basic schists and gneisses mostly of igneous origin, granite batholiths of more than one period of intrusion and highly metamorphosed slates and quartzites. The pre-Huronian has not been completely subdivided into stratigraphic units and its various members have not been traced and correlated over the entire region.

The Huronian is separated into two units by an unconformity far less pronounced than the one at the base of the Huronian. Individual beds of both divisions have been traced successfully from district to district. The lower division, called the Bruce

[1] W. H. Collins, "The Geology of Gowganda Mining Division," *Canada Geol. Surv. Mem. No. 33* (1913), 121 pp., 4 pls., 5 figs.

[2] W. H. Collins, "The Huronian Formations of Timiskaming Region, Canada," *Canada Geol. Surv. Mus. Bull. No. 8* (1914), 27 pp., 2 maps, 1 fig., 1 pl.

series, consists of a thin basal conglomerate, white quartzites with interbedded, well-sorted conglomerates, an impure siliceous limestone, and some graywacke, whose maximum thickness is more than three thousand feet. The upper division, or Cobalt series, includes tillites, quartzites, graywackes, a few thin impure limestone beds and grades upward into pure quartzites. It has in part the characteristics of glacial till associated with stream and quiet-water deposits contemporaneous with glaciation. Locally it shows minor unconformities. The local terms, Bruce and Cobalt series, rather than Lower Huronian and Upper Huronian, are applied to these divisions because their full equivalence to these units in the original Huronian is regarded as doubtful.

Collins[1] advocates that a local classification of the pre-Cambrian rocks of the Timiskaming region be adopted and that their correlation with other districts be postponed until they are better known. He emphasizes the importance of the unconformity at the base of the Cobalt series as major plane of division. The various series are classified by him as pre-Huronian and Huronian. His classification follows:

Keweenawan	Diabase Sudbury norite	Huronian
	Intrusive contact	
	Whitewater series	
	Lorrain series	
	Local unconformity	
	Cobalt series	
	Great unconformity	
	Batholithic granite intrusive	Pre-Huronian
	Intrusive contact	
	Sudbury, Timiskaming, Fabre series	
	Unconformity	
	Granite intrusives	
	Keewatin group	

Collins[2] reports that hitherto unknown granites intrude the Bruce and probably the Cobalt series along the coast of Lake Huron.

[1] W. H. Collins, "A Classification of the Pre-Cambrian Formations in the Region East of Lake Superior," *Congrès Géologique International XII.* Session 1914, pp. 399–407.

[2] W. H. Collins, "The Age of the Killarney Granite (Ontario)," *Canada Geol. Surv. Mus. Bull. No. 22* (1916), 12 pp., 1 pl., 1 fig.

Collins[1] reports on the Onaping map area about fifty miles north of Sudbury. Following his former practice, he divides the pre-Cambrian rocks into Huronian and pre-Huronian. His table of pre-Cambrian formations follows:

Huronian—Keweenawan Olivine diabase
Basic intrusives ? Quartz diabase
Quartz norite and intermediate varieties
Intrusive contact
Cobalt series—Upper white quartzite
Banded cherty quartzite
Lorrain quartzite
Gowganda formation:
Conglomerate
Graywacke
Limestone
Great unconformity
Pre-Huronian
Batholithic intrusives—Granite gneiss and its differentiates
Schist complex—Altered volcanic and intrusive rocks, iron formation, and other sediments

P. E. Hopkins[2] reports the succession in McArthur township of the Porcupine Gold Area as

Late intrusives—Diabase
Timiskaming ?—Slates
Laurentian—Granites intrusive into Keewatin
Keewatin—Greenstone, serpentine, hornblende schists, porphyries, carbonates, and chert magnetite iron formation

Hopkins[3] reports on the Beatty-Munro Gold area in the Larder Lake mining division of Ontario, latitude 48° 30′, longitude 80° 15′. The rocks are all pre-Cambrian and are classified by Hopkins as follows:

Post-Timiskaming intrusives—Feldspar porphyry dikes
Intrusive contact
Diabase dikes and stocklike masses
Intrusive contact

[1] W. H. Collins, "Onaping Map Area (Ontario)," *Canada Geol. Surv. Mem., No. 95* (1917), 157 pp., 11 pls., 8 figs., 2 maps.

[2] P. E. Hopkins, "Notes on McArthur Township," *Ontario Bur. Mines, 21st Ann. Rept.*, Vol. XXI (1912), Part I, pp. 278–80, 2 figs.

[3] P. E. Hopkins, "The Beatty-Munro Gold Area (Ontario)," *Ontario Bur. Mines, Ann. Rept.*, Vol. XXIV (1915), Part I, pp. 171–84, 9 figs., 1 map.

Timiskaming series—slate, graywacke, quartzite conglomerate, and schistose derivatives

Igneous—Feldspar porphyry—relation to Timiskaming uncertain—intrudes Keewatin

Intrusive contact

Keewatin—Amygdaloidal and ellipsoidal basalt, diabase, serpentine, iron formation, and breccia, with metamorphosed equivalents

The gold occurs as free gold and as tellurides in quartz veins cutting Keewatin and Timiskaming rocks. The veins contain high-temperature minerals, viz., pyrrhotite and tourmaline.

Kindle and Burling[1] conclude that the escarpment of pre-Cambrian rocks which overlooks the plain of Paleozoic sediments north of the Ottawa and St. Lawrence rivers is due to normal faulting, the sediments being on the downthrow side. The facts which indicate this are: (*a*) the presence of Paleozoic outliers resting on a hummocky surface of pre-Cambrian rock north of the escarpment, the corresponding Paleozoic beds south of the escarpment being about seven hundred feet lower, (*b*) the extreme regularity of the escarpment, (*c*) the absence of Paleozoic re-entrants along the escarpment, (*d*) the lack of clastic material from the limestone adjacent to the pre-Cambrian rocks of the escarpment, (*e*) the dissimilarity of the escarpment features with other nearby pre-Cambrian borders where normal erosion has even yielded an escarpment of Paleozoic rocks, (*f*) the escarpment is at the northern border of a zone in which subsidence or normal faulting is characteristic.

Knight[2] finds the following succession of pre-Cambrian rocks in the Thessalon area on the north shore of Lake Huron to the west of Killarney. This is the original Huronian area of Logan.

Diabase dikes intersecting Nipissing

Keweenawan—Diabase

Intrusive contact

Nipissing diabase, similar to that at Cobalt and Gowganda—shows local gradations into pink micro pegmatite. Thessalon greenstone, a fine-grained basal sometimes amygdaloidal

Intrusive contact

[1] E. M. Kindle and L. D. Burling, "Structural Relations of the Pre-Cambrian and Paleozoic Rocks North of the Ottawa and St. Lawrence Valleys," *Canada Geol. Surv. Mus. Bull. No. 18* (1915), 23 pp., 2 pls., 6 figs.

[2] C. W. Knight, "The North Shore of Lake Huron," *Ontario Bur. Mines, Ann. Rept.*, Vol. XXIV (1915), Part I, pp. 216–41, 13 figs.

Animikean—1. Pink quartzite and arkose with thin beds of jasper conglomerate similar to Lorrain series at Cobalt
2. Slatelike graywacke—beautifully and thinly bedded
3. Conglomerate, graywacke, slatelike graywacke, quartzite, arkose

Great unconformity

Algoman—Granite, massive, and at times gneissoid

Knight[1] and others report on the Abitibi-Night Hawk Gold Area southeast of Cochrane on the Canadian National Railway. The succession includes Keewatin rocks consisting of basic pillow lavas, rhyolites, basalt, diabase, hornblende, and chlorite schists, which are overlain by slate graywacke, quartzite, conglomerate, and iron formation. These Keewatin rocks are intruded by diabase and gabbro, peridotite and pyroxenite, granite and other acid rocks, quartz diabase and olivine diabase dikes.

In 1911[2] A. C. Lawson restudied the Rainy Lake area which he had reported on in 1887. In 1887, Lawson reported that the pre-Cambrian rocks of this region were all Archean and that the succession from the bottom upward is as follows:

A series of clastic sediments metamorphosed to mica quartz schists and paragneisses called the Coutchiching. This series is conformably overlain by the Keewatin, consisting dominantly of amygdaloidal and ellipsodial greenstone lava flows, chloritic schists, and other basic rocks of a similar nature. The Coutchiching and Keewatin were intruded by batholithic masses of granite and granite gneisses and allied acid igneous rocks which caused the doming up of the rock into which they were injected.

The restudy of the Rainy Lake area by Lawson in 1911 was occasioned by the fact that the United States Geological Survey and the International Committee of 1898 did not accept Lawson's conclusion that there existed a Coutchiching series of rocks stratigraphically below the Keewatin. This dissent from the opinion of Lawson was based on field work by Van Hise in various parts

[1] C. W. Knight, A. G. Burrows, P. E. Hopkins, and A. L. Parsons, "Abitibi-Night Hawk Gold Area," *Ontario Bur. Mines, 28th Ann. Rept.* (1919), 84 pp., maps, and illustrations.

[2] "The Archean Geology of Rainy Lake," restudied by A. C. Lawson. *Canada Geol. Surv. Mem. No. 40* (1913), 111 pp., geological map in pocket, 9 pls., 1 fig.

of the Rainy Lake area, and in consequence of the examination of the Coutchiching series on the east end of Shoal Lake and along parts of the Seine River by the International Committee of 1898. The International Committee found that the so-called Coutchiching of Lawson on the east end of Shoal Lake consisted of conglomerates and other clastic sediments which unconformably overlie the Keewatin. They then concluded that all of the rocks mapped by Lawson as Coutchiching are not below the Keewatin.

In consequence of Lawson's restudy of 1911, he persists in classifying the rocks of the Rainy Lake area as Archean. He holds to this classification because he regards it as historically correct, having been, he claims, the usage of Logan in his map of the north shore of Lake Huron, and furthermore, he believes that the erosion interval which intervenes between the rocks of the Animikie series and those which precede it is the most conspicuous in the pre-Cambrian rocks of the Lake Superior region. He believes that the rocks on the far side of this erosion interval show greater metamorphism and more intense folding and a larger number of intrusions than those on the near side of this interval.

On re-examining the Coutchiching rocks on the east side of Shoal Lake, he finds that the conclusions of the International Committee are correct for this particular locality. He finds no evidence, however, to change his original conclusion regarding the Coutchiching which is wrapped around domes of intrusive granite and which dips under the Keewatin at a low angle in the region of Rice Bay and around Bear's Passage. Lawson's classification of the rocks of the Rainy Lake district follows.

Keweenawan—Diabase dikes	
Algoman	Granite, porphyritic, and syenite gneisses, and a basic facies of syenite
Huronian (Seine series)	Lamprophyric rocks Quartzite and slate, and schists Conglomerate
Laurentian—Granite and granite gneiss	
Archean Keewatin	Anorthite Hornblende gabbro Limestone (one seam) Greenstone, greenstone schists, felsite, sericite schist, ash beds, agglomerate, siliceous slates and schists, chert, mica schist
Coutchiching mica schist, paragneiss, and phyllite	

Lawson[1] classifies the pre-Cambrian rocks of Steeprock Lake, Ontario, as follows:

Algonkian	Keweenawan
	Erosion interval
	Animikie
	Eparchean interval
Archean	Granite gneiss, intrusive in the Seine series
	Irruptive contact
	Seine series
	Acute deformation and erosion interval
	Steeprock series
	Erosion interval
	Granite gneiss, intrusive in the Keewatin
	Irruptive contact
	Keewatin
	Coutchiching

The Steeprock series comprise interbedded sediments and irruptive rocks: dark-gray slate, agglomerate, greenstones and green schists, conglomerates, and limestone. Van Hise and Leith have correlated them as Lower Huronian.

Lawson describes certain radial calcareous and siliceous fossil structures of the limestones. The rays of these fossils extend to a roughly circular limit in section normal to the axis of the organism. In oblique sections, the border is usually elliptical. In some cases, they are cornucopia-shaped, the rays sometimes showing conical or elliptical septa. The rays vary from one to fifteen inches in length.

The paper is supplemented by descriptive notes on the fossils by W. D. Walcott.

Miller and Knight[2] discuss the metallogenetic epochs of Ontario. Most of the metal production comes from Keweenawan rocks and consists chiefly of silver, nickel, and copper in the order named. Next in importance are the Algoman gold-bearing granite intrusions which have been productive at Porcupine and many other places. The Keewatin has furnished a small tonnage of iron ore.

[1] A. C. Lawson, "The Geology of Steeprock Lake, Ontario," *Canada Dept. of Mines, Mem. No. 28* (1912), 23 pp., 2 pls.

[2] W. G. Miller and C. W. Knight, "Metallogenetic Epochs in the Pre-Cambrian of Ontario," *Ontario Bur. Mines, Ann. Rept.*, Vol. XXIV (1915), Part I, pp. 244–48, map; *Roy. Soc. Canada Trans.*, 3d Ser., Vol. IX (December, 1915), Section IV, pp. 241–49, 1 fig. (map).

Erosion has destroyed much ore. Some ore has been preserved by folding and faulting.

Miller and Knight's[1] classification of the pre-Cambrian of Ontario follows.

Keweenawan

Unconformity

Animikean

Includes rocks called Animikie heretofore, also Logan's type section, and the Cobalt and Ramsay Lake series. Minor unconformities occur within the Animikean

Great unconformity

(Algoman granite and gneiss

Igneous contact)

Laurentian of some authors, the Lorrain granite of Cobalt, and the Killarney granite of Lake Huron

Timiskamian

Includes sedimentaries of various localities heretofore called Huronian—also the Sudbury series of Coleman

Great unconformity

Same order as that at base of Animikie

(Laurentian granite and gneiss)

Igneous contact

Loganian { Grenville (sedimentary)
Keewatin (igneous)

The authors differ from Collins and Coleman in that the latter recognize a twofold division of the Animikean group. Other differences are largely a matter of names and emphasis on the relative importance of various features. Lawson, Coleman, and Collins emphasize the unconformity at the base of the Animikean and recognize two major groups. Miller and Knight stand alone in concluding that the Grenville of southeastern Ontario is in part interlayered, but largely above the Keewatin. Other authors are either less confident or express doubt as to the position of the Grenville.

Parsons[2] describes the productive iron deposits of the Michipicoten district.

[1] W. G. Miller and C. W. Knight, "Revision of Pre-Cambrian Classification in Ontario", *Jour. Geol.*, Vol. XXIII (1915), pp. 585–99.

[2] A. L. Parsons, "The Productive Area of the Michipicoten Iron Ranges (Ontario)," *Ontario Bur. Mines. Ann. Rept.*, Vol. XXIV (1915), Part I, pp. 185–213, 22 figs., 3 pls., maps.

Quirke[1] maps the Española area representing the eastward extension of the original Huronian. His classification of the pre-Cambrian follows.

Great unconformity	
Huronian	
Keweenawan—Diabase injection	
Igneous contact	
Cobalt series	
Gowganda formation—Massive slate	
Conglomerate member	400 feet
Graywacke slate	400 feet
Bedded conglomerate	650 feet
Unconformity	
Bruce series	
Serpent quartzite	8,000 (?) feet
Española group	
Española limestone	25 feet
Española graywacke	280 feet
Bruce limestone	150 feet
Slight unconformity	
Mississagi quartzite	4000 feet
Great unconformity	
Pre-Huronian	
Granite intrusions	
Igneous contact	
Basic intrusions	
Igneous contact	
Schistified sediments	

Large-scale maps were made by Stansfield[2] of certain mica, apatite deposits in the townships of Hull and Buckingham of Ottawa Valley. The pre-Cambrian rocks underlying this area comprise:

Igneous intrusives
- *c*) Trap dykes
- *b*) Gabbro and pegmatites of the mineral deposits
- *a*) Older pegmatite veins

Grenville series
Ottawa gneiss

The Ottawa gneiss includes granite and syenite gneiss, crystalline limestones, quartzites, garnet-gneisses, sillimanite gneisses,

[1] Terence T. Quirke, "Española District, Ontario," *Canada Geol. Surv. Mem. No. 102* (1917), 75 pp. 6 pls., 8 figs., map.

[2] John Stansfield, "Certain Mica, Graphite, and Apatite Deposits of the Ottawa Valley," etc., *Canada Geol. Surv. Summ. Rept. 1911* (1912), pp. 280–85.

and certain unidentified gneisses have been listed as the constituents of the Grenville series in this area.

The Cobalt series[1] comprises a basal conglomerate, resting on a nearly level surface and an assemblage of arkose, quartzite, graywacke, and argillite. Gradations are found in both vertical and horizontal directions. The finer-grained bedded varieties are assigned to a lacustrine origin. The heterogeneous, angular conglomerates with "soled," and occasionally striated pebbles are believed to be glacial.

The Larder Lake[2] district located on the boundary between Ontario and Quebec, about thirty miles north of Lake Timiskaming shows the following succession of rocks, according to Morley E. Wilson:

Pleistocene and recent
  Gravel, sand, clay, and till
Huronian
  Conglomerate
  Graywacke
  Arkose
  Conglomerate
 Igneous contact
  Diabase, gabbro, syenite porphyry; the first two probably time equivalents of similar rocks in the Cobalt district
Laurentian
  Granite, gneiss, granodiorite, pegmatite, aplite
 Unconformity

Keewatin—Greenstones and greenstone schists largely of effusive origin, Larder slate and dolomite quartz porphyry, rhyolite and aplite intrusive into the preceding	Pontiac schists composed of biotite and quartz. Relation to Keewatin unknown

 Igneous contact

Wilson[3] argues against widespread correlations of pre-Cambrian rocks and urges that for the present local names should be given to series and formations.

[1] Morley E. Wilson, "The Cobalt Series: Its Character and Origin," *Jour. Geol.*, Vol. XXI (February–March, 1913), pp. 121–41, 3 figs.

[2] Morley E. Wilson, "Geology and Economic Resources, Larder Lake District, Ontario," *Canada Geol. Surv. Mem. No. 17* (1912), 62 pp., 11 pls., 5 figs., 2 maps.

[3] Morley E. Wilson, "Sub-Provincial Limitations of Pre-Cambrian Nomenclature in the Saint Lawrence Basin" (Abstract), *Bull. Geol. Soc. Am.*, Vol. XXIX (1918), pp. 90–91.

[*To be continued*]

Reviews

Oil Investigations in 1917 and 1918. Bulletin 49. Illinois Geological Suivey, 1919. Pp. 144.

The volume consists of five papers bearing on the oil and gas of Illinois. The first, "Petroleum in Illinois in 1917 and 1918," by N. O. Barret, contains statistics of the economic phase of the oil industry. The salient facts, as summarized in the report, are (1) that in 1917 Illinois fell in rank from fourth to fifth among oil-producing states, due to the actual decline that same year in Illinois production, and to the enormous increase in oil production in Kansas in that year; (2) that in 1918 with further decrease of production in Illinois and a notable increase in production in Louisiana, Illinois fell to sixth place as far as quantity was concerned; (3) that evidence of the high grade of Illinois oil is found in the fact that Illinois ranked fourth and fifth in value of product in 1917 and 1918, when it ranked fifth and sixth in quantity of oil produced.

The three following papers, "Brown County" and "Goodhope and Laharpe Quadrangles," by Merle L. Noble, and "Parts of Pike and Adams Counties," by Horace N. Coryell, are reports dealing with the geology of the areas mentioned with particular reference to oil and gas possibilities. All the reports have good structural maps. In the areas described there are four possible oil and gas horizons, (1) the Pottsville conglomerate, (2) the Niagaran dolomite, (3) the Hoing sand (Silurian, just below the Niagaran), (4) the Maquoketa shale and Galena Platts-ville limestone or dolomite (Ordovician). The Hoing sand has furnished the best showing of oil, but prospecting in it is hazardous, owing to the discontinuous and lenticular nature of the sand. The other formations have furnished only slight showings of oil and gas in this territory. In Warren County gas occurs in small quantities in the glacial drift; the gas probably was derived from the decomposition of vegetable matter buried in the drift, and no large amounts are to be expected.

The fifth paper, "Experiments in Water Control in the Flat Rock Pool, Crawford County," by F. B. Tough, S. H. Williston, and T. E. Savage (in co-operation with the U.S. Bureau of Mines), is a statement of investigation and work done in regard to corrective work in water control in oil wells. Various aspects of the problem are discussed, including the use of mud fluid and cement in water control. R. A. J.

Recent Publications

—Grover, N. C. Surface Water Supply of the United States, 1916. Part XII. North Pacific Drainage Basins. A. Pacific Basins in Washington and Upper Columbia River Basin. [U.S. Geological Survey, Water-Supply Paper 442. (Prepared in co-operation with the states of Washington, Montana, and Idaho.) Washington, 1919.]

—Grover, N. C., *et al.* Surface Water Supply of the United States, 1917. Part IV. St. Lawrence River Basin. [U.S. Geological Survey, Water-Supply Paper 454. (Prepared in co-operation with the states of Minnesota, Wisconsin, New York and Vermont.) Washington, 1919.]

———. Surface Water Supply of the United States, 1916. Part VI. Missouri River Basin. [U.S. Geological Survey, Water-Supply Paper 436. (Prepared in co-operation with the states of Colorado, Montana and Wyoming.) Washington, 1919.]

———. Surface Water Supply of the United States, 1917. Part VIII. Western Gulf of Mexico Basins. U.S. Geological Survey, Water-Supply Paper 458. (Prepared in co-operation with the state of Texas.) Washington, 1919.]

———. Surface Water Supply of the United States, 1916, Part X. The Great Basin. [U.S. Geological Survey, Water-Supply Paper 440. (Prepared in co-operation with the states of Utah, Nevada, California, Oregon, and Wyoming.) Washington, 1919.]

———. Surface Water Supply of the United States, 1916. Part XII. North Pacific Drainage Basins. B. Snake River Basin. [U.S. Geological Survey, Water-Supply Paper 443. (Prepared in co-operation with the states of Oregon, Nevada, and Washington.) Washington, 1919.]

—Grover, N. C., and Hoyt, W. G. Surface Water Supply of the United States, 1917. Part V. Hudson Bay and Upper Mississippi River Basins. [U.S. Geological Survey, Water-Supply Paper 455. (Prepared in co-operation with the states of Minnesota, Wisconsin, Iowa, and Illinois.) Washington, 1919.]

—Harker, Alfred. Petrology for Students. An Introduction to the Study of Rocks under the Microscope. 5th ed., revised. [Cambridge: University Press, 1919.]

—Harnsberger, T. K. The Geology and Coal Resources of the Coal-bearing Portion of Tazewell County, Virginia. [Virginia Geological Survey, Bulletin No. 19. (Prepared in co-operation with the U.S. Geological Survey.) Charlottesville, 1919.]

—Hawaiian Volcano Observatory, Monthly Bulletin of the. Vols. VI and VII. [Honolulu, 1919.]

—Heikes, V. C. Gold, Silver, Copper, Lead, and Zinc in Arizona in 1918. [U.S. Geological Survey, Mineral Resources of the United States, 1918. Part I, Sec. 15, pp. 329–68. Washington, 1920.]

———. Gold, Silver, Copper, Lead, and Zinc in Nevada in 1918. Mines Report. [U.S. Geological Survey, Mineral Resources of the United States, 1918. Part I, Sec. 12, pp. 217–64. Washington, 1920.]

—Henderson, C. W. Gold, Silver, Copper, Lead, and Zinc in New Mexico and Texas in 1917. [U.S. Geological Survey, Mineral Resources of the United States, 1917, Part I, Sec. 24. Mines Report. Washington, 1919.]

———. Gold, Silver, Copper, Lead, and Zinc in New Mexico and Texas in 1918. Mines Report. [U.S. Geological Survey, Mineral Resources of the United States, 1918. Part I, Sec. 14, pp. 303–28. Washington, 1920.]

———. Gold, Silver, Copper, and Lead in South Dakota and Wyoming in 1918. [U.S. Geological Survey, Mineral Resources of the United States, 1918, Part I, Sec. 8. Washington, 1919.]

—Hewett, D. F. Manganese and Manganiferous Ores in 1917. [U.S. Geological Survey, Mineral Resources of the United States, 1917, Part I, Sec. 23. Washington, 1919.]

—Hill, J. M. Arsenic, Bismuth, Selenium, and Tellurium in 1918. [U.S. Geological Survey, Mineral Resources of the United States, 1918, Part I, Sec. 9, pp. 193–99. Washington, 1919.]

———. Gold, Silver, Copper, Lead and Zinc in the Eastern States in 1918. Mines Report. [U.S. Geological Survey, Mineral Resources of the United States, 1918, Part I, Sec. 11, pp. 211–15. Washington, 1920.]

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Summaries of Pre-Cambrian Literature of North America. Papers V–VII. By EDWARD STEIDTMANN.

Features of a Body of Anorthosite-Gabbro in Northern New York. By WILLIAM J. MILLER.

A Glacial Gravel Seam in Limestone at Ripon, Wisconsin. By F. T. THWAITES.

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Diastrophism and the Formative Processes. XIV. Megadiastrophism. By T. C. CHAMBERLIN and R. T. CHAMBERLIN.

VOLUME XXVIII NUMBER 8

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DIASTROPHISM AND THE FORMATIVE PROCESSES

XIII. THE BEARINGS OF THE SIZE AND RATE OF INFALL OF PLANETESIMALS ON THE MOLTEN OR SOLID STATE OF THE EARTH

T. C. CHAMBERLIN
University of Chicago

In the last article of this series[1] it was found (1) that the solar gases, as they were expelled to form the planetary systems, were so mixed that they were unfitted to form solid bodies such as the terrestrial planets, the planetoids, and the satellites, until after they had been sifted by a selective process, (2) that the sifting process introduced such a serious departure from familiar modes of gaseous condensation as to require reinterpretation, (3) that the process of concentration was also complicated by inherited motions, (4) that it was still further conditioned by the formation of precipitates and precipitate aggregates, and (5) that the planetary cores, while in process of formation, were subjected to viselike squeezing, more intense below than above, followed by partial relaxation, so that selective extrusion attended the closing processes, involving the ascent of the lighter mobile matter and the compression and reorganization of the rest, thus contributing

[1] "Diastrophism and the Formative Processes. XII. The Physical States of the Planetary Nuclei during Their Formative Stages," *Jour. Geol.*, Vol. XXVIII (1920), pp. 473–504.

toward high density, rigidity, and elasticity in the central parts. It was further found that the shapes of the planetary cores were influenced from the very outset by the gyratory system of circulation that attended their formation, and that they thus failed to take on strictly spherical forms, so that they were likely to yield unsymmetrically to the heavy masses later built upon them by planetesimal growth. Even the primitive circulation thus had its influence on the diastrophism that developed much later.

Let us now consider the planetesimal growth. This involves (1) a study of the nature of the planetesimals at the start, (2) the conditions that affected the mode and extent of their growth, and (3) the modes and rates of their infall and the effects of these on the molten or solid state of the earth, as also on its content of explosive gases.

THE NATURE OF THE PLANETESIMALS AT THE START

The way in which the planetesimals are supposed to have arisen has been made clear in previous articles, but it will facilitate our present study to note that they took their starts from two main sources: (1) solar molecules driven into orbits by the original solar expulsion, and (2) molecules thrown out into orbits from the nuclei later by molecular interaction. There were other sources of planetesimals, but they may be neglected here. In both classes the planetesimals started as molecules chiefly. To some extent they may have been newly formed precipitates from the solar gases, or precipitate aggregates formed by the union of the fresh precipitates. Such precipitates are thought to form in the sun's photosphere now. They would be likely to have been formed by the expansion of the solar gases just after these emerged from solar pressure. The essential point here is that, whether molecules, precipitates, or precipitate aggregates, they were minute. Whether they afterward grew to notable sizes depended on the conditions that controlled their later history. Chief among the controlling influences were the dynamic properties given the planetesimals by their expulsion, and the gravitative stresses that controlled the field into which they were driven. It is to be kept ever in mind that they were bodies projected into swift independent flight, each

in its own path under control of its own inertia and the gravitative stresses of its environment. The planetesimals shot out from the nuclei had the simpler history, and are easiest followed to gain typical pictures of planetesimal behavior as a basis for estimates of their modes and rates of infall.

Let us picture the earth nucleus as pursuing a nearly circular orbit about the sun while certain of its outer molecules were escaping from it in various directions by reason of exceptional velocities given them by cumulative successions of rebounds from favorable collisions. It is easy to fall into the error of supposing that these molecules, thus escaping in different directions, would take orbits quite discordant with that of the nucleus and thus pass into the meteoritic rather than the planetesimal class. As constituents of the nucleus, they already had motions relative to the sun, and of course carried these with them they went into orbits of their own, except in so far as these motions were reduced or increased by their ejection from the nucleus. The velocity of the nucleus in its orbit should have been of the order of eighteen miles per second, and that of all the molecules of the nucleus about the same, some a little more, some a little less, by reason of their participation in rotation, et cet. It was the new and additional velocity which the escaping molecule had been given, *measured at the border of the sphere of control of the nucleus*, which determined its orbit after it had escaped. Only in extremely rare cases would molecular interaction give to an escaping molecule a speed greater than the parabolic velocity respecting the nucleus, that is a velocity sufficient to carry the molecule to infinity so far as the restraining attraction of the nucleus was concerned. The parabolic velocity of even the full-grown earth at the border of its sphere of control is 1.75 miles per second, so that we leave a large margin of safety if we assume that molecules almost never were shot away from the border of the sphere of control of the nucleus at more than two miles per second. Now, as the nucleus was moving at eighteen miles per second relative to the sun, a molecule shot directly backward would still have a velocity of sixteen miles per second relative to the sun, and a molecule shot directly forward would have a velocity of twenty miles per second relative to the sun, while

those shot out at lesser velocities, or sidewise at various angles, would have intermediate velocities. All would therefore be moving in the same general direction as the nucleus and their orbits would still be similar. The molecules in these new orbits would therefore be planetesimals, because they would revolve about the sun in orbits similar to those of the planets. The kinetic theory of gases requires us to suppose that molecules of the lighter gases escaped from the outer border of the earth-nucleus with some degree of frequency while it was hot and diffuse, and that such molecules have continued to escape from the outer border of the earth's atmosphere ever since, but much less frequently. And so of all other planets that have atmospheres, and of the sun as well. Practically all the molecules that thus escaped into orbits still remained within the sphere of control of the sun and were liable in time to be picked up again, so that this whole system of escape and recovery constitutes a mode of exchange of atmospheric material between the domains of the sun and the planets. It contributes to the maintenance and equilibrium of our atmosphere as elsewhere set forth.[1]

Let us now look to the gathering in of the planetesimals in this typical case, for that is the vital point here. Under the laws of mechanics the planetesimals shot forth in this way would come back to the virtual points of their escape at the end of each revolution in their new orbits, unless they were diverted by some intervening influence. From this it is easy to jump to the conclusion that they would all soon be picked up again by the nucleus, but not so, in general. They were nearly all thrown into larger or smaller orbits and that determined the *time* at which they should get back to the point of their origin. In most cases this was either earlier or later than the return of the nucleus and hence recapture was avoided. Figure 1 and the accompanying periodic data, prepared by Dr. MacMillan, make this very clear. From the point A at the top of the figure let one molecule be shot forward at a speed 10 per cent greater than that of the nucleus and let another molecule be shot backward so that its velocity shall be 10 per cent less than that of the nucleus. The first molecule will take the outer

[1] *The Origin of the Earth* (1916), pp. 13–17.

orbit, the second, the inner orbit. The molecule in the inner orbit will get back to *A* in .77 of the time required by the nucleus to reach this point, while the molecule in the outer orbit will require 1.424 times that period, i.e., if it takes the nucleus three hundred and sixty-five days to complete its orbit, the planestesimal that was shot backward and took the inner orbit would reach *A* eighty-four days ahead of the nucleus, while the molecule that was shot ahead and took the larger orbit would return to *A* one hundred

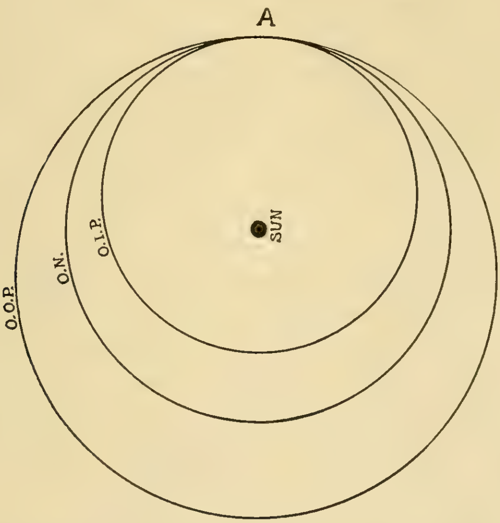

FIG. 1.—O.N. represents the orbit of the nucleus; O.O.P., the orbit of the outer planetesimal; O.I.P., the orbit of the inner planetesimal. Periodic times, earth = 1; inner planetesimal = 0.77; outer planetesimal = 1.424 (MacMillan).

and fifty-five days after the nucleus had passed. There was therefore no immediate danger of collision and recapture in either case. Only by waiting for a concurrence of the schedules, which would be liable to be thwarted by perturbations, or by a protracted series of orbital shiftings, or by changes of orbital form or dimensions, could this be brought about.

Were these planetesimal molecules likely to unite with one another in the course of their flights and so grow to larger sizes? The figure illustrates this point also. It is very obvious that the two planetesimals specified have no opportunity at all to unite

with one another until they return to the vicinity of A. But one of them would reach A two hundred and thirty-nine days earlier than the other. Even in this specially favorable case when they had a common node there was no immediate opportunity for union. Of course cases of less divergence could be chosen in which there was a nearer coincidence of orbits and of time schedules, and if there were many orbits there would be some real crossings farther from the nucleus, but those chosen illustrate the prevalent fact that even though such bodies have similar orbits and sometimes actual crossings, they may yet remain independent for long periods. Their mutual attractions would, in general, aid in bringing this about ultimately, but instead of this they might be brought into co-ordinate orbits like those of the earth and moon and revolve together in harmony indefinitely. At best the process was likely to be a very slow one. The picture of molecules drawn directly together, as in the case of static bodies or of gases, is very commonly substituted for the real case, and is very misleading. When all possible cases are considered, as well as the multitude of planetesimals, there are enough chances of collision and coalescence, especially with the nuclei, to make the process of ingathering effective in the course of long periods, but in its very nature it cannot be a speedy process. When planetesimal molecules or even precipitate aggregates collide, rebound would be more likely to follow than coalescence, unless they were electrically charged. Coalescence almost inevitably follows collision with nuclei but not encounters between planetesimals.

This simple example of the evolution and behavior of planetesimals illustrates the mechanism by which they are maintained and the contingencies of their capture or their mutual coalescence, where the conditions are exceptionally favorable. For the case most important in the formation of the earth, we must turn to the solar molecules which were driven directly into orbits by the original propulsion from the sun under the stimulus and attraction of the co-operating body. These were subject to the law of return to the points of their origin, but they were greatly diverted by the pull of the co-operating body and so largely lost all such systematic relations to a given nucleus as those that made the previous case

so simple and instructive. The orbits in this case were distributed through greater space and more irregularly, and hence their coalescence with one another and their capture by the planetary nuclei, as a rule, required greater changes in the forms, dimensions, and attitudes of their orbits. We will turn to concrete specifications and numerical values presently.

THE SIZE OF PLANETESIMALS NOT IMPORTANT IN RESPECT TO MELTING EFFECTS

Lest we stress the growth of planetesimals too much, it is prudent to observe at once that the sizes of the planetesimals were not matters of vital moment so far as the total energy-effect of their infall was concerned, for whatever was gained by concentration of mass was lost by less frequent infalls. On the whole, less energy available for conversion into heat was carried into the earth by the united planetesimals than by the same mass ununited, for in coming together, energy of motion was converted into heat and this was dissipated at the point of union in open space; the combined mass carried so much less energy into the earth-core. However, whenever combination took place, there was relatively less resistance and heating of the atmosphere in plunging through it, and so relatively more heating of the surface of the earth. As we shall see a little later, however, the chief effect at the earth's surface was lateral dispersion and an elastic or explosive reaction, resulting in a great scattering of débris with little obvious melting. None the less, we shall consider the melting effects of large planetesimals as well as small ones.

THE LIGHT SHED ON SIZE BY EXISTING PLANETESIMALS

It has been shown in previous papers[1] that the union of molecules and the growth of small aggregates could take place with more or less facility up to a certain order of size, but that beyond such order conditions unfavorable to further growth arose and increased relatively, so that indefinite growth was probably limited, as a general rule. It appeared that chemical, electrical, and

[1] Article X, this *Journal*, Vol. XXVIII, No. 2 (February–March, 1920), pp. 140–44.

cohesive attractions functioned effectively in the early stages; but that fragmentation, abrasion, and exfoliation came into increasing effectiveness as larger sizes were attained. Theoretically, then, growth from the minute state at which the planetesimals started, took place presumably up to limited sizes with relative facility, beyond which the presumption of much larger growth was adverse, except under unusual conditions. Theory, however, does not define at all closely where the balance between the opposing agencies was to be found, and so we turn to naturalistic evidence which is more decisive.

1. *The zodiacal planetesimals.*—It is an accepted view that the zodiacal light is due to the reflection of solar light from minute solid or liquid particles distributed in a lenslike form about the sun. The central plane of the lens is essentially coincident with the common plane of the planetary system. The outer border of the lens reaches to some undetermined distance beyond the earth. Under favorable conditions, it is possible to trace the counterglow (*Gegenschein*), on the side of the earth opposite the sun, into continuity with the zodiacal light on the sunward side. It is not improbable that the edge of the lens is extremely attenuated and extends indefinitely outward in the plane of the planets. The form and extent of the lens in the planetary plane make it scarcely less than certain that the particles are sustained by orbital dynamics, and that the orbits are of the planetary type and that hence the particles are planetesimals. This warrants us in turning to them for light on the sizes and masses of planetesimals. Their testimony is obvious for they are certainly quite small.

Though they envelop the earth and must in many cases be quite near, the individual planetesimals are too small for detection. Although they are certainly very numerous, their joint mass is not known to affect the motions of any body. They are interpreted either as remnants of the original planetesimal system, or as more recent products due to the projection of solar matter so close to the planets that it is drawn forward by them into elliptical orbits about the sun. If the first view is correct, or in so far as it is correct, the planetesimals are exceptionally old and should

have reached the fullest growth to which they are ordinarily subject. If they are of more recent origin, they merely bear testimony to the common size to which planetesimals of the younger order attain. But as they are so obviously minute their testimony in either case is weighty.

2. *The satellitesimals of Saturn's rings.*—Satellitesimals are merely special forms of planetesimals. It is convenient to distinguish between them in certain cases, while in other cases the generic term planestesimal is most satisfactory. In the Saturnian case, they are notable for their very close association with one another and for their definite borders. These hint at a special origin, perhaps the disintegration of a satellite by the differential attraction of Saturn, since they lie within its Roche limit. At any rate, the closeness of the individual satellitesimals to one another gives them rather pointed bearing on the question of growth to large sizes, for their nearness to one another should favor this, if mutual attraction has any appreciable effect. According to Bell's studies of their albedo, they are chiefly very minute particles.[1] Only rarely is there evidence of masses reaching as much as a meter in diameter. Trituration as a consequence of their mutual collisions is probably the dominant size-controlling agency in this case.

3. *Precipitate aggregates formed from condensing gases. The chondrules.*—When the gases or vapors of stony and metallic substances mixed with lighter gases were expelled from the sun into the vacuum of interplanetary space, they must probably have been greatly expanded and cooled and the stony and metallic substances thrown down as precipitates at successive stages according as the appropriate temperatures were reached. As each gaseous substance was diffused through the others, the precipitates could at first have been little more than molecular in size, but by subsequent interaction, in the fashion of Brownian particles, the first precipitates were brought into contact with one another and in their fresh, hot, viscous states should have united into larger aggregates rather freely. In so far as they solidified, they naturally

[1] Louis Bell, "The Physical Interpretation of Albedo, II, Saturn's Rings," *Astrophys. Jour.*, Vol. L (July, 1919), pp. 1–22.

took the form of concretions or of crystals. I have ventured to suggest that this may be the mode in which chondrules—little organized bodies that enter into the formation of 90 per cent of known meteorites—were formed. Later I shall suggest that the formation of the common small meteors of the sky may have taken place in practically the same way as planetesimals, i.e., by the progressive aggregation of precipitates from the stony and metallic ingredients of solar gases shot into interplanetary space and there cooled, the distinction between the two being their orbital characters and planetary relations. If these suggestions are in the line of truth, the chondrules give very specific evidence on the usual sizes of planetesimals, for they range from the size of a walnut down to fine dustlike particles.

4. *The negative evidence.*—Concurrent with these concrete sources of evidence, supported by theory, is the significant fact that no bodies of a distinctly larger or *planetoidal* order of magnitude are seen to revolve in the region of the earth's orbit or within it. We have found reasons for suspecting that the normal dynamic stresses in this inner solar region have always been too great to permit the collective aggregation of precipitate clouds of so little mass. At any rate, the negative testimony of observation stands against any view that postulates an abundance of bodies of planetoidal size in the region of the earth or their effective participation in the formative processes of the earth or the moon.

Let us then assume that the chondrules are our best naturalistic guide in respect to the normal sizes of planetesimals. For definiteness in the computations that follow, let us assume as a convenient representative weight, one-fiftieth of a pound, say one-third of an ounce, or about 9 grams. In testing the probability, or otherwise, that planetesimal infalls would produce a molten state of the growing earth-core, it will make no essential difference whether the planetesimals were somewhat larger or somewhat smaller than this size which is adopted merely for definiteness and convenience. After inspection of the melting effects in a case thus made as nearly normal as we conveniently can, we will try to test the effects of supposedly larger planetesimals.

THE TIME OVER WHICH THE INGATHERING OF PLANETESIMALS WAS SPREAD

It is obvious that the time over which the infall of planetesimals was spread is an essential factor in determining whether the heat of their infall would melt the earth surface or not. And so if there are any naturalistic evidences bearing on this point, they should be brought under consideration at once so that they may serve as guides or tests where assumptions have to be made in trying to deduce the period of infall from the mechanics of the case. Successful study of earth history has been found to rest much more largely on naturalistic considerations than on deduction, especially when the premises involve so much that is assumptive. An approach along naturalistic lines may be found in biologic evolution combined with geologic chronology.

1. *The intimations of biologic evolution.*—It seems to be the consensus of opinion among those best fitted to judge that the portion of life-evolution that has taken place since the faunas and floras of the early Paleozoic offered a fair criterion for judgment, is of the order of one-tenth of the total life-evolution, or some such proportion. This proportion will therefore be made the basis of the time-scale used in the following discussion. It will be easy to modify the results of the computations to suit any other proportion that may be thought nearer the reality. I do not think that any other proportion which is tenable will change the general tenor of the conclusions, so far as these bear on the melting effects of planetesimal infall.

Two geologic time-scales are now in use, an older one built on estimates of the present rates of geological progress, and a newer one built on radioactive processes. For myself I regard the latter as much the more trustworthy. The former seems to me to need radical correction (1) for the exceptional speed of present denudation due to the stripping of very large portions of the surface of its native protection, and (2) for the exceptional speed induced by the present high relief of the surface brought about by recent diastrophism.[1] But let us use both scales. Those who prefer

[1] See Article VIII of this series, "The Quantitative Element in Circumcontinental Growth," this *Journal*, Vol. XXII (1914), pp. 516–26.

the old scale will doubtless concede that the *proportions* of the radioactive scale may be used safely as a means of extending the older scale over the Proterozoic and Archean eras, where its own criteria are not available. Using the radioactive scale, the beginning of the Paleozoic may be placed, in round figures, at 4×10^8 years ago, the beginning of the Proterozoic at 12×10^8 years, and the oldest portion of the Archean that has been determined in respect to age, at 16×10^8 years. Using the old scale, the beginning of the Paleozoic may be placed at 10^8 years and—using the radioactive scale for proportionate extension—the beginning of the Proterozoic at 3×10^8 years, and the earliest determined Archean at 4×10^8 years. To fill out the *total* period of life-evolution on the radioactive scale, an allowance of 24×10^8 years *previous* to the earliest determined Archean must be made, making the total life-period 4×10^9 years. To similarly fill out the total period of life-evolution on the old scale, 6×10^8 years is to be allowed previous to the earliest determined Archean, and 10×10^8 years for the whole life-period.

In thus using the proportions of biologic evolution as an indication of the period over which the growing stage of the earth was spread, it is to be noticed that, to avoid making the assigned period of planetesimal infall unfairly long by including too much of the tailing-out stage, I shall consider all planetesimals that fell during the last 400,000,000 years (radioactive scale) of the Archean era, and all that have fallen since, 16×10^8 years in all, as though they had fallen within the computed period. On the other hand, all that fell during the nuclear stage, i.e., before a definite earth-core was formed, are necessarily excluded from the estimated period of life-evolution, since the conditions were incompatible with life. No doubt the infall during the distinctly nebulous portion of the nuclear stage may have been more rapid than during the biologic stage but that does not concern us in considering the period of biologic activity preceding the earliest age-determined Archean. It is the special merit of the planetesimal hypothesis that it takes due account of biological requirements, as generously interpreted as the leaders in biological inquiry demand. The biological

evidences are regarded as among the most cogent that bear upon the duration of the early history of the earth.

Qualified and defined as thus specified, the period of effective planetesimal infall subsequent to the nuclear stage is made to range from 600,000,000 years on the old geological scale, to 2,400,000,000 years on what seems to me to be the more probable radioactive scale.

These assignments of time may impress some readers as very long, but the question is to be asked anew, are they longer than the biological evidence requires? We shall soon inquire whether they are any longer than the mechanics of the case warrant. But before passing on, it is to be noted that the interpretation of biological evolution should no longer suffer from duress due to supposed limitations of time, such as were vigorously urged during the last half of the last century by advocates of the contractional theory of the sun's heat and of other physical tenets which were really less well grounded than the biological and geological interpretations. This alien stress is now not only lifted, but a new theoretical urgency of precisely opposite import has taken its place, a seemingly imperative need to find a source of heat for the maintenance of the stars of such potency as will enable them to serve their indicated functions in the protracted history of star clusters and our stellar galaxy. For this, a stellar longevity of the order of ten billion years, or some such great period, seems to be required. Short of trespassing on some such time allowance as that, biology and geology cannot be said to be necessarily restricted for lack of solar endurance. The seeming demand of biological and geological evidences for a total earth age of three or four billion years need not be thought extravagant or unreasonable, if either class of evidence is found to really require it.

2. *The intimations of the planetesimal mechanism.*—Let us now turn to the planetesimal mechanism to see what may be its most probable time requirements. Neglecting planetesimals of high and unusual orbital range, a fair and at the same time conservative working approximation to the extent of that portion of the planetesimal field which was tributary to the earth, may be made by

taking the width of the tract now occupied by the planetoids as its breadth, and for its depth the limits of the earth's dominant attraction in competition with that of Mars on the outside, and that of Venus on the inside. These give roundly 55×10^6 miles in breadth and 58×10^6 in depth. They define the cross-section of the planetesimal ring which curved around the sun with the path of the earth-core near its center. The actual field was much larger than this, but the planetesimals outside these limits are neglected to compensate for any lateral thinning inside. The area of the cross-section was therefore roundly 3×10^{15} square miles and its curved length 292×10^6 miles. For a working case of the medium order, let the mass of the earth-core, at the beginning of the specified period of planetesimal infall, be taken as one-third of the final earth-mass, leaving two-thirds of the earth-mass in the form of planetesimals to be gathered in. It will be seen that this proportion makes the mass of the planetesimals large and favors effective infall. It is taken merely as a fair working basis without any intention of implying an opinion as to the ratio of the nuclear to the planetesimal portions which actually obtained; that may best be reserved for further study. Taking the masses and dimensions of Mars and Venus as guides, in accordance with our comparative studies (Article X), the earth-core should have had a diameter of about 6,000 miles. Its disk would then have an area of 28×10^6 square miles, roundly. This is the fleeting target which the widely scattered planetesimals must hit, if they were to take part in the earth-building, or to change the simile, this is the area of the sweeper that must gather in the planetesimals from their vast field to build its one-third mass up to a three-thirds mass.

1. As rigorous treatment is impracticable, modes of approximation are our only recourse; and so, as a simple and purely artificial first approach, suited to give a realistic impression of the immensity of the field that must be swept, let us suppose that the planetesimals stand still while the earth-disk sweeps through it at its normal speed, changing its path in such an effective way as to clean up an entirely new swath at each revolution. Even by this impossibly speedy method, 100,000,000 years, roundly, would be required.

2. To make a first approach of a natural kind that can be treated mathematically, Dr. MacMillan has suggested that the planetesimals might be treated as though they were particles of gas which would close in upon the track of the earth-core as it revolved through the center of the tract, though the dynamics of gases are radically different from those of planetesimals, and corrections must be made accordingly. To gather in all the planetesimals under these conditions would take an indefinite period; to gather in 90 per cent would require somewhat over 260,000,000 years. Keeping in mind that this is not the real case, but merely one that can easily be treated, it is worth while to note that one-fifteenth of the earth-mass would fall in after 260,000,000 years had passed and that nine-fifteenths would be systematically distributed over this period with infall greatest at the start in due proportion, but it does not give warrant for excessive concentration in the early stages. If that is assumed, it makes the more certain a non-melting rate in the later stages and the infall during these would furnish the outer shell of the earth to a depth beyond the reach of most problems of immediate geologic interest. The vital point, however, is that in this substitute case, like the real one, the laws of mechanics require a distribution of infall over long periods.

3. The next step toward the real case is the substitution of heterogeneously revolving particles for the previous gaseous particles. A gaseous organization is a failing structure in the sense that when any inner portion of it is removed the rest collapses sufficiently to fill the space. In an orbital organization no such collapse takes place, each remaining body is sustained in its orbit by its own moving force. This makes a radical difference in the rate of ingathering by a body like the earth-core in the case in hand. Those planetesimals whose paths had actual crossings with that of the earth-core would be picked up, if not disturbed by perturbation, whenever their time schedules became coincident at the crossing, but not before, normally. Those planetesimals—by far the greater number—which had no such actual crossings at the start, would circle through their independent orbits indefinitely,

if they were not thrown out by collision, which would be rare in such vast space, or perturbed by other bodies, among which the earth-core would be the most influential in most cases. But such perturbations work very slowly, and their effects on the orbits involved are not easily visualized by any except experts in orbital dynamics. It is easy, however, to see that the case is far different from the direct collapse of gaseous particles and that it must occupy much greater time. In the lack of any rigorous determination of just how much longer the ingathering process would take, we may merely note that if it be taken as no more than two or three times longer, the total period would at least equal the biological requirements given above on the older geological scale.

But such bodies in heterogeneous orbits belong to the meteoritic type, and would not arise normally from the dynamic influences postulated by the planetesimal hypothesis, nor would their aggregation give rise to planets in concurrent revolution, for lack of the requisite moment of momentum, unless it were assigned them by some supplementary hypothesis such as revolution of the whole assemblage. As in the preceding case this assumption only serves as a step toward the real case.

4. The distinctive feature of the postulated planetesimals was that *they were moving in the same general direction as the collecting body and at the same general rate of speed.* The process of collection was therefore confined to overtakes and to convergencies of orbits. The differences between this and the preceding case may be compared to the different degrees of danger of collision between automobiles when, in one case, they are running in a common direction, on the right side of the road, under fairly well regulated speeds, and, in the other case, running wildly at random in both direction and speed. So planetesimals, circling about the sun in more or less concurrent orbits, only collide and coalesce in so far as they deviate from concurrence with the rest of the system or are perturbed in their independent orbits and drawn into coalescence by overtakes or convergencies. In so far as their orbits were concurrent, the moment of momentum of the combined mass was nearly as high as the sum of the individual moments of momenta, and so, if at any stage the orbits became adjusted to one another, they

might revolve in harmony indefinitely, as do the earth and moon. It was this concurrency of movement that made the evolution of a planetary system highly endowed with moment of momentum a possibility. Therein lies the soul of the planetesimal theory. But evolution under these conditions requires great lapses of time.

But lest this be overstressed, it is to be noted that the subparallelism of orbits and the subequality of speeds gave greater effect to the mutual attractions of the earth-core and the planetesimals, and so tended either to bring them together or else into harmoniously adjusted orbits, such as those of the earth and its satellite. Compared with the much more familiar gaseous and meteoritic types, the fundamental tendency of a planetesimal system is *not so much direct concentration as concurrent revolution*, though, in so far as the nuclei are competent, they gather in the smaller bodies. It seems clear, therefore, that the time required for collecting the planetesimals would be some multiple of that assigned in the preceding case. It is not clear just how large it would be, but if taken at three or four, the total time requirement would equal the maximum estimate of the biological requirement. In the nature of the case, it should not be less, for life-evolution could not proceed until a solid core was formed and the rate of infalling planetesimals permitted a congenial temperature. At any rate, however large may be the latitude for different numerical estimates of the total time and rate of planetesimal infall, it is altogether clear that a precipitate ingathering is incompatible with the mechanics of the planetesimal system.

THE RATES OF PLANETESIMAL INFALL

a) *The infall of normal planetesimals.*—We have already found reasons for thinking that the planetesimals were usually small, as their name implies, and have chosen one-fiftieth of a pound as a working figure. We have also chosen one-third of the total mass of the earth as the amount of material already in the earth-core and two-thirds as the amount still in the form of planetesimals at the beginning of the specified period of infall.

The mass of the present earth is 6×10^{21} tons. There would then be 4×10^{26} planetesimals of the specified mass to be gathered

into the core to complete the growth of the earth. The earth-core, taken at 6,000 miles in diameter, would have a surface area of 3×10^{15} square feet. As there were 4×10^{26} planetesimals in all, 13×10^{10} planetesimals must fall upon each foot of earth-core surface, on the average, to build the body up to its present mass.

Now, if we take the total period of infall, as given above on the radio-geo-biologic scale, at 2.4×10^9 years, a planetesimal one-fiftieth of a pound in weight, falling upon each square foot every 6.7 days, or a little less than once a week, would have completed the growth of the earth in the time specified. It will be agreed, I think, that this does not remotely approach a rate sufficient to melt the earth surface. If there is any doubt as to the dissipation of energy following the impact of a falling body, see later discussions.

If we take as the period of infall the biological requirements as estimated on the older geologic time-scale, 6×10^8 years, a planetesimal falling upon a square foot once in about forty hours would build the earth up to its present mass in the time estimated. This again, I think it will be agreed, is not near the melting-rate for the general surface.

If we make the time of infall equal to the highest of our range of estimates from the mechanics of the case, 3×10^9 years, an average fall of a planetesimal on each square foot once in a little over eight days would suffice, or if we take the minimum of the estimates, 18×10^8, a planetesimal once in about five days would answer, in either case far from a general melting-rate.

If we fall back upon the untenable assumption that the planetesimals distributed themselves after the manner of gaseous particles—made merely as a first step in approach—and take the computed 26×10^7 years as the total time, the average rate of infall upon each square foot would be about one planetesimal in seventeen hours. Even this does not seem to be a rate that would threaten the melting of the earth, and yet it is much more rapid than is permitted by the mechanics of the real case under the basal assumptions made.

Let us now reverse the mode of inquiry by trying to approximate a rate of infall that would cause the melting of the earth surface, and then compare results with those reached in the preceding ways.

If the mass of the earth-core equaled one-third that of the present earth, an atmosphere of sufficient depth to protect its surface from the direct impact of planetesimals of the specified mass would have surrounded it. The melting of the earth must then have hung upon the competency of the infall to so heat the upper atmosphere as to melt the earth surface some miles below. About half the heat acquired by the thin upper air would have been quite promptly radiated outward and the melting left to the other half. The effect of the air on meteorites plunging into it is suggestive in this connection. As soon as a film of meteorite-substance becomes viscous enough to yield to the high pressure of the air condensed on the meteorite's front by its high speed, the film is driven backward and dissipated along the meteor's path forming the "streak" of the "shooting star." Only a very small part is melted at any one instant, or left in any one spot. Even this minute part only reaches the first stages of the molten state and hence is very quickly cooled again to the solid state. To apply this to planetesimals, it is to be noted that the mean velocity of meteorities is probably four or five times that of normal planetesimals, and their moving energies sixteen to twenty-five times as great in proportion to mass. The working picture, then, in the case in hand, is that of a little mass, one-fiftieth of a pound, making a similar but feebler streak of quickly heated, quickly cooled matter, down the center of a column of air one square foot in cross-section. This must take place in such close succession as to melt one square foot of the earth surface at the bottom of the atmosphere in spite of outward radiation. To really complete the picture, it is necessary to add that the lower atmosphere would soon be filled with the dust of the dissipated planetesimals and the melting of the surface would have to be effected through this screen. It seems clear that to effect general melting the upper atmosphere must be heated throughout to the melting-point of average rock-substance, and kept at that temperature in spite of

convection and radiation. As radiation increases with the fourth power of the temperature, it would be very effective as the red-hot stage was approached.

As the case is beyond the reach of experiment or rigorous computation, specific estimates of rate can be little more than matters of judgment. Let us therefore resort to the serial method, which sometimes leads to a decisive conclusion even when definite quantitative values are unavailable.[1] Let each reader fix upon such rate of infall as seems to him competent to produce a molten state of the earth surface under the given conditions. Let us then see how such a rate fits into the range of rates which the mechanics of the case permits. Too great a discrepancy may be about as decisive as if the precise rates were known. The working test is the final arbiter.

If one's assumption is that a planetesimal plunged into the upper end of each square-foot air-column once every second, the column would be built up to the present surface in 4,119 years. It will be recalled that our first, but wholly arbitrary and exceptionally speedy mode of sweeping up the planetesimal field required 100,000,000 years and the most speedy natural method 260,000,000, and that both of these hypothetical cases required less time than the real case.

If one planetesimal fell upon each square foot once per minute, the total time would still be only 247,140 years. The competency of such a rate to melt the earth surface would, I think, at least be open to question.

If the rate were one planetesimal per hour, the total period would be 14,828,400 years, which is about one-seventeenth of the time of ingathering required on even the gaseous assumption. Moreover this rate would give a cooling period to every column of air more than 3,000 times as long as the glowing period, estimated from the mean duration of "shooting stars."

At one planetesimal per day per square foot, the total time would be 355,881,600 years. I think it will be agreed that this rate of infall would fall far below a liquefying rate, and yet even

[1] "The Methods of the Earth Sciences," *Pop. Sci. Mo.* (November, 1904), pp. 70 and 71 ("The Method of Multiple Series").

so fast a rate of infall as this does not seem to be warranted by the mechanics of the case.

Apparently the only line of escape from the import of such a serial trial lies in postulating that the rate of infall in the earliest stages was sufficiently more rapid than the mean rate to effect melting in such early period. A declining rate of infall is, of course, to be presumed, and has been taken into account. The rate used in the computations is the mean rate for the specified accession when assumed to be distributed over only the period which *followed* the formation of the earth-core and *preceded* the earliest time-determined Archean, 16×10^8 years ago. The accessions before that period were reckoned as part of the mass of the earth-core, and the accessions since were thrown into the specified period to avoid counting the long tailing-out period of 1,600,000,000 years (radioactive scale). The period thus made the basis of computation represents an intermediate stage of infall and was given the benefit constructively of all subsequent infall. We excluded such infall as was contemporaneous with the evolution of the nucleus from its nebulous state until a definite earth-core was formed, because it necessarily preceded life-evolution, and because it is not separable from nebulous condensation and the other nuclear conditions. In connection with the irregularities of the original outburst, there may have arisen some incalculable rates of infall. These would doubtless have made themselves felt chiefly in the nuclear stages. Our endeavor was to include in the computations only the systematic ingathering into which the action settled as a secular process. The physical state of the nucleus during its evolution from a nebulous state into an earth-core has been left an open question, reserved for further consideration. Meanwhile, a molten state during that period has been treated as one of the alternatives, and as a not improbable one. The infall of planetesimals during that stage may probably have been an important factor in determining the state which actually prevailed. But all that is held to antedate the growth of the outer part of the earth. This embraces about all that has yet been brought under study in geological and biological inquiries. To reach a satisfactory basis for these inquiries is the soul of the present issue. The state of

the core does not radically affect most geological and petrological problems.

The infall of supposedly large planetesimals.—In the foregoing tests it has been assumed that planetesimals normally grew to about the same order of size as the chondrules, and that the disruptions and abrasions they suffered after reaching this size kept them down to about the order of the little masses that form "shooting stars." Let us now consider the melting effects likely to follow if the planetesimals had grown to very much larger sizes. To keep as close to the actual as practicable, let us base our first study on the phenomena of Coon Butte, or Meteor Crater, Arizona, interpreted as the work of a gigantic meteorite, or cluster of meteorites or, if you please, the nucleus of a comet, accepting as conclusive, in the main, the disclosures of the drillings, shafts, and trenches of Barringer and Tilghman. Then, let us base our second study on the craters of the moon, on the assumption—made solely for the sake of the study and without acceptance—that they were formed by the impacts of still larger bodies.

Case I. The testimony of Coon Butte or Meteor Crater.—There is no reason to think that the celestial mass whose plunge into the earth formed Coon Butte was a planetesimal, because, among other reasons, it came from the northward, an unlikely direction for a planetesimal and because its indicated velocity was probably too high. The work done by it, however, is very instructive respecting the physical effects of such a falling mass under natural conditions.

The essential phenomena are a circular rim of upturned strata, covered thickly by outthrown débris, 130 to 160 feet above the surrounding plain, inclosing a crater nearly 4,000 feet in diameter and 440 feet deep, measured from the original surface of the horizontal sandstone and limestone from which the crater was formed to the top of the present partial filling.[1] Crushed rock, mingled

[1] The following are among the more important papers on the subject: A. E. Fotte, *Amer. Jour. of Sci.*, Vol. XLII (1891), p. 413; also *Proc. Amer. Assoc. Adv. Sci.*, Vol. XL (1892), pp. 279–83; G. K. Gilbert, *13th Ann. Rept.*, *U.S. Geol. Surv.*, Part I (1892), p. 98; *14th Ann. Rept.*, Part I, (1893), p. 187; *Geol. Soc. of Wash.* (President's Address), March, 1896; *Science* (N.S.), Vol. III (1896), pp. 1–13; O. A. Derby, "Constituents of the Canyon Diablo Meteorite," *Amer. Jour. of Sci.*, Vol. XLIX

with meteoritic matter, lies below the floor of the crater to a depth of about 660 feet. Below this, disrupted rock seems to grade into undisturbed sandstone at points between 1,100 and 1,200 feet beneath the general plain. Rock masses and clastic material, coarse and fine, were thrown from the pit and strewn over the adjacent plain for distances of one to two miles on all sides, while meteoritic matter, distributed subconcentrically, reaches out to an extreme distance of $5\frac{1}{2}$ miles. The rim and pit, while subsymmetrical, have sufficient asymmetry to indicate an infall from a northerly direction, perhaps N. NW. to S. SE. The chief mechanical effects were the formation of the crater by the breaking up of perhaps 8×10^8 tons of rock, and the hurling out of perhaps half of it, the turning up to high angles of the previously horizontal limestone and sandstone beds of the crater-border, the crushing of large quantities of sandstone to silicious rock flour, and the development of some schistosity in connection with it. The chief thermal effects were the partial metamorphism of some of the rock flour and the development of incipient fusion in other portions of it, some of this portion becoming vesicular. The crushing and heating were obviously the direct effects of the impact, the upturning of the rim and projection of the débris as obviously the effects of the attending lateral thrust and the quasi-explosive reaction that followed.

The energy involved in the mechanical effects must be subtracted from the total energy of the impact before the heating effects can be theoretically deduced. The very large sum total of these mechanical effects shows how great would be the error of computing the energy of infall in terms of heat and using that as

(Feb., 1895), pp. 101–10; D. M. Barringer and B. C. Tilghman, "First Mention of the Discovery that the Crater Is an Impact Crater and Not a Crater Produced by a Steam Explosion" (President's Statement), *Proc. of Acad. Nat. Sci.* (Philadelphia, Dec. 5, 1905); D. M. Barringer, "Coon Mountain and Its Crater," *Proc. Acad. Nat. Sci.* (Philadelphia, Dec., 1905), pp. 861–86 (issued March 1, 1906); B. C. Tilghman, "Coon Butte, Arizona," *ibid.*, pp. 887–914; J. W. Mallet, *Amer. Jour. of Sci.*, Vol. XXI (May, 1906), pp. 347–55; J. C. Branner, *Science*, Vol. XXIV (Sept. 21, 1906), pp. 370–71; H. L. Fairchild, at Tenth Session of the International Geological Congress, in Mexico, September 14, 1906, *Compte Rendu, X Session, Congrès Géol. Inter.* (Mexico, 1906), p. 147; O. C. Farrington, "Analysis of Siderite Oxides or Iron Shale," *Amer. Jour. of Sci.*, Vol. XXII (Oct., 1906), pp. 303–9.

a measure of the melting effects. This would be a tempting line of attack but is quite inadmissible because the mechanical effects alone call for more energy than can be reasonably assigned to the meteoritic material found. The only safe recourse is the direct evidence. The heating effects implied by the direct evidence are singularly small compared with the mechanical effects. To a considerable, but not closely determined, extent, the crushed sandstone shows incipient schistosity with partial metamorphism, obviously a compressive effect, the heat of which did not rise to the grade of fusion. To a considerably smaller extent, if I interpret the descriptions correctly, the crushed sandstone shows the early stages of fusion, while some of this portion has become inflated and pumaceous, but no appreciable masses were left in the state of glass or other completely fused product. If fully melted matter was formed at all, it was probably dispersed by the explosive reaction. It seems quite clear that the portion which became vesicular did not become fully fused and fluent, for, in part at least, the bedding lines were not wholly obliterated. These portions seem, however, to have been rendered distinctly viscous and susceptible of inflation. This must probably have taken place during the resilience which followed the compression. The internal gases could scarcely have puffed the viscous rock while the intense pressure of the impact was on. If, on the other hand, they had remained viscous until the pressure from the falling back of the exploded débris was brought to bear, they would have collapsed, at least in all deeply buried portions. Apparently they had cooled in their inflated state while the pressure was off. It seems, therefore, that there was practically no liquid rock left when the explosive reaction was over. This is a matter of radical importance in its bearings on the question of producing a holo-liquid earth by such impacts. It shows that a very high proportion of the energy of impact was converted into another mechanical form, not into heat. There is no question about the greatness of the energy of impact; the mechanical work involved in the formation of the crater and of its rim, as also in the crushing and scattering of the débris, demonstrate that. And yet there is no evidence that this violent impact left even the smallest pool of lava. *The significant feature of the*

case lies in its clear evidence that the energy of impact was chiefly transformed into lateral thrust and resilience of quasi-explosive type. Confessedly the most outstanding problem left is to find a source of energy adequate to the mechanical effects so impressively forced on attention. The case still remains something of a puzzle on that account. Meteoric matter has been found so widely disseminated through the débris, both within and without the crater, that the origin of the crater is no longer in doubt, but yet the amount of meteoric matter thus far brought into evidence seems clearly too small to be adequate. The suggestion of Barringer that the infalling mass was a cluster of meteorites or a comet's head is plausible in itself—and the orbits of comets are such as to make a bump into the earth a recognized contingency—but these suggestions give little help in the matter of adequacy. A larger mass than has been found seems to be required to satisfy the effects realized. For such computations as I have made, a siderite sphere 400 to 500 feet in diameter was taken, but it is scarcely worth while to give the results here. They are of the same import as those of the next case.

We ought not to overlook the fact that this is the only known case of such an infall in the history of the earth. This is an embarrassment in postulating a rapid series of infalls. Nor is its negative bearing merely a surface matter. If such a crater had been formed and buried in a natural way in any geologic formation, however old, there would be a fair chance of its detection. There is therefore a complete absence of geological warrant for supposing that infalls of this kind were ever anything but very sporadic affairs. If Meteor Crater was formed by the impact of the nucleus of a comet, theory would make its repetition an extremely rare event. The concept of an enormous meteorite, or close cluster of meteorites, other than cometic, has no observational basis. If the views respecting the origin of meteorites, later expressed in this article, have any cogency, the infall of such bodies would be governed by the same order of chances as those of comets. From no point of view, therefore, does Meteor Crater offer substantial ground for supposing that the earth was once molten because of the impacts of meteoritic bodies.

Case II. The questionable intimations of the craters of the moon.—The impact theory of the craters of the moon affords a concrete basis for the study of infalls of a still larger order. To fit this case, bodies of the order of five miles in diameter, more or less, seem to be required, and for working convenience these may be given the specific gravity of the moon, 3.34. The assumed size in this case has about the same ratio to the larger order of the moon's craters that the assumed 400 or 500 foot meteoritic body had to the size of Meteor Crater, but the mass is made relatively less to be in better accord with the moon's mass. The size is about the lower limit assigned to planetoids. No atmosphere can be supposed to have broken the effects of infall in this case or to have checked the free dispersal of the débris.

In the previous case there was surprisingly little evidence of liquefaction. What is the evidence here? The steep walls of the deep craters are quite incompatible with a liquid state, so far as this outermost part is concerned and this is the part subject to direct impact. There was strength enough in the crust to support the lunar Alps and Apennines, some of whose peaks tower to heights of 20,000 feet and more above the adjacent surface, i.e., 5,000 feet higher than their terrestrial prototypes. No less than ten mountain ranges have been recognized on the moon, which implies general crustal strength. The great relief of such elevations towering above such depressions is uncontrovertible evidence of strength and stability. The significance of this is emphasized, if the supposed impacts are made a part of the formative process of the moon, for then they are very old and have stood in this strong relief in spite of all the creep of the geologic ages.

A search for direct evidences of molten matter gives meager results under the most favorable interpretation that is tenable. Such of the craters as have level bottoms have been thought to imply a partial filling of lava, supposed to have risen from below after the craters had been formed. These bottoms may, however, be interpreted as level beds of clastic débris, like those that form the level bottom of Meteor Crater. So, also, the seemingly smooth, but really quite accidented, plains of the "maria" have been interpreted as great lava flows, but these may likewise be merely débris

plains. In the best photographs they are seen to have considerable relief and to be crisscrossed in different directions by lines of débris obviously shot from neighboring craters. They are thus at least surficially covered with clastic débris. But granting that everything which appears at this distance like lava really is lava, the whole does not imply a liquefaction of the moon of any other order than that signified by the great lava flows on the earth whose essential solidity is now beyond question.

But let us look at the question of rapid infall quantitatively and numerically. Let us assume that at the beginning of the accretion process, one-third of the mass of the moon was already in its core, while the remaining two-thirds had been gathered into bolides five miles in diameter which were yet to fall in. The mass of the moon is about 732×10^{17} tons. There would then have been 244×10^{17} tons in the moon-core and 488×10^{17} tons in the bolides yet to fall in. The mass of each of these bolides would have been about 997×10^{9} tons, and their total number about 49×10^{6}. Their individual volumes would have been a little over sixty-five cubic miles, while the volume of the moon-core would have been about 14×10^{8} cubic miles, and the radius of the core 708 miles. As the radius of the full-grown moon is 1,080 miles, the core would have had to grow radially 372 miles.

Now the surface area of the moon-core would have been 6×10^{6} square miles, while the disk of the five-mile bolides was a trifle less than twenty square miles in area, so that there would have been over 300,000 disk-areas on the surface of the moon-core. It would thus have required less than two hundred bolides to each disk-area to complete the full growth of the moon.

The liquid-forming impact theory now takes a critical form. We have seen that the surface of the moon shows that the last craters were not attended by general liquefaction or even a viscous state of their immediate walls. The last falls, however, were accelerated by nearly the full mass of the present moon, while the first falls were accelerated by only one-third the mass of the moon. The individual effects of the last infalls should, therefore, have been greater than any that preceded. They should also have inherited whatever benefits were transmissible from previous

infalls, in proportion to the time between falls. As these last impacts left no conclusive evidence of molten residue, it follows that no previous infall, in itself, can be consistently supposed to have left any greater molten residue and if their inheritance was greater it could apparently only come from a closer succession of infalls. Apparently, then, the only way in which a general molten condition can reasonably be supposed to have arisen was from the cumulative effects of such inherited residues of heat from the earlier infalls in excess of those of the later infalls. How tenable is this? There were by computation less than two hundred infalls of the specified kind to each disk-area during the whole accretion period of the moon. If that accretion period were essentially the same as that of the earth, as it should theoretically be, and if we compute the rate of infall by using the minimum accretion period assigned the earth based on mechanical and biological evidences, to make the rate as high as consistent, the mean interval between impacts would be about 3,000,000 years. If the mean accretion period had been used, the mean interval between infalls would have been more than twice this time. Very little inheritance of heat from a surficial bump can be postulated over an interval of this order.

But we are not left wholly to computations on estimated requirements. There is the direct evidence of the craters themselves. Some are fresh and their débris lines lie straight across older pits and older features of all sorts. Some pits and rims are worn or buried to the very limit of recognition, and there are all grades between. These features offer no warrant for the hypothesis that there was a closely crowded infall. They distinctly imply that the formation of the visible craters stretched over a long period. This evidence is the more cogent when the limited means of denudation, owing to the absence of an atmosphere and hydrosphere on the moon, are considered.

Now let us turn to the theory itself. If it be supposed that the five-mile bolides are planetesimals, the supposition itself hides under its cloak a quasi-assertion of the rate of their infall, for, as we have seen, all planetesimals started as very minute bodies controlled by a system of dynamics that imposed upon them slow growth as a

necessity of the limited amount of planetesimal matter, the large amount of space through which it was distributed, and the mutual relations of the planetesimal orbits, as already brought out. There were besides obstacles to growth beyond quite small sizes. Even if these obstacles be supposed to have been ineffectual, time for growth from the minute sizes to five-mile bolides must have intervened before the latter could function as crater-formers. They could thus have come into function only at a late stage. But accretion could not have been suspended in the meantime. They could therefore have come into function only as a *partial* source of lunar accretion. Growth from the smaller planetesimals must have gone forward during all the intervening period. Accretion simply by such giant planetesimals is thus incompatible with the fundamental conditions postulated by the basal hypothesis on which it rests.

The hypothesis is not much more promising if planetoids are substituted for the supposed giant planetesimals, for, by the mechanics of the case, the planetoids were given courses less favorable to aggregation than were the planetesimals, and hence greater intervals between their infalls must in consistency be assumed. This is in harmony with the observed fact that at least eight hundred planetoids are still following their own individual paths in a relatively limited tract and yet no collision or even dangerous approach to one another has been noted during the whole period of astronomical observation. In addition to this, we have found reasons for doubting whether planetoids could organize as nuclei of the planetary type under the differential stresses of the solar attractions that prevail in the region of the earth and in regions still nearer the sun.

The hypothesis that the pits of the moon were formed by the impacts of great meteorites offers no presumption that one infall would be followed by another in the same spot within any short period. As a cause of general melting, this is even more unpromising than the preceding.

The discussion thus far has proceeded on the assumption that the pits of the moon are the scars left by the impacts of great bolides of one sort or another. Before turning to the next topic,

it may be well to forestall misapprehension by making clear our view that such an origin of the craters of the moon is in itself improbable, for bodies moving in orbits under the control of the sun should plunge into the moon, if they strike it at all, at various angles to the vertical. In many cases the stroke should be quite oblique to the surface and should leave elongated pits, unsymmetrical rims, unequal dispersions of débris, and other tell-tale features; all the more so because the moon had no atmosphere to retard and turn downward the path of the bolides. Apparently the only escape from these grave objections lies in supposing that the explosive reaction was so great that it completely overwhelmed the effects of the direct stroke. If this assumption were tenable, it would seem to imply that the explosive dispersion was so great that it must have scattered all mobile matter, and especially all liquid matter so effectually as to insure its cooling while in flight.

THE SIGNIFICANCE OF THE EXPLOSIVE PHENOMENA OF THE MOON

The moon seems to have been a paradise of Krakatoas and Katmais. Interpreted as the product of gaseous explosion, the abundance and the greatness of the craters of the moon carry special significance. They have commonly been thought to imply a once molten state of the moon. I think the argument lies in precisely the opposite direction. If the moon, in its formative stage had been a molten globe, its high temperature should have set free all gases susceptible of being freed by any temperature that ever arose afterward. Its liquid state and its convective circulation would have brought these gases to the surface and given them opportunities of escape never equaled later, for the high temperature of the surface would have forced unsurpassed molecular activity and have insured their escape from the control of the moon. Even the cold full-grown moon cannot hold the volcanic gases. After all such gases had been boiled out of the moon and had escaped, and the gas-free lava had cooled, the moon should have been devoid of the means of explosive action.

On the other hand, if the moon were built up of minute clastic particles which carried such amounts of occluded and combined gases as meteorites do, and as they naturally would from their

long flights in the ultra-atmospheric field of the sun, and if the porous surface of the moon received and held by adsorption, chemical combination, or otherwise, molecular planetesimals of the gas-forming order, such as would inevitably plunge into it from the interplanetary field, there would be entrapped in the body of the moon, as it grew, a supply of disseminated gas-producing material sufficient to actuate great explosions whenever concentrated later by conditions favorable for such action. As the moon grew, its self-compression and the strains developed within it by neighboring bodies should have forced this potentially gaseous material toward the surface and developed the conditions of eruption. The moon should also have inherited its quota of radioactive substances and these should have played their part in the lunar vulcanicity. The fragmental constitution of the outer part of the moon, postulated as an inevitable feature of an accretional origin, should have rendered it specially susceptible to explosive effects. More or less local lava-production, as well as the quiet type of vulcanism, are entirely consistent with this view of the exceptionally gaseous eruptions, and they are postulated, but the evidence of the moon's surface seems to give this more quiet action a place quite subordinate to the gaseo-explosive phase.

THE SIGNIFICANCE OF TERRESTRIAL VULCANISM

The inferences that seem so imperative in the case of the moon apply also to the gaseous phases of vulcanism on the earth. The argument is a little less imperative because the earth is able to hold an atmosphere and would probably do so to some less extent in a molten state, and so, if it were once in that state, volcanic gases could have been retained in its liquid mass sufficient to balance the partial pressures of the like gases in such lessened atmosphere as the earth then held. The amount of gases so held in equilibrium could not have been large, and such as existed would not have served as explosive agencies because of the very fact that they were held in balance by opposing pressure. They were there merely because there was an outside pressure holding them there and that outside pressure was never removed under normal conditions. It seems merely declaiming the obvious to say that

such a gas content is incompetent to produce explosive eruptions and that such eruptions occur on the earth only when there are special developments or accumulations of gas within or beneath the exploded matter. In a molten earth, stirred during its long cooling stages by effective convection,[1] the gases set free by the various stages of heat of that period should have been so far brought to the surface and dissipated by molecular activity—except the limited equilibrium amount—that the earth when cooled and solidified should have been as deficient in explosive material as lavas are now found by experiment to be when melted in the open air at the surface and, after a long stage of boiling, cooled to the solid state. In essence, therefore, the case of the earth is the same as that of the moon. The studies of terrestrial volcanoes of recent years have brought forth accumulating evidence that volcanoes are actuated by inborn rather than outside gases, and that they are essentially independent of one another, though of course not independent of common conditions. Their explosiveness seems thus clearly due to their own individual resources and has no obvious dependence on any molten zone, sheet, pool, or other remnant of a once pervasive liquid state.

THE TESTIMONY OF THE ABERRANT BODIES OF THE SOLAR SYSTEM

We have now considered at some length the bearings of various lines of evidence drawn from the normal elements of the solar system. Let us turn for a moment to such suggestions as may be derived from the aberrant members of the system, the meteors, meteorites, and comets. If these are merely aliens that have been introduced incidentally from foreign sources, as some of them may be, there is little reason to expect them to teach much relative to the domestic organization; but if they were born in the system and are products of its dynamics, they may be quite as instructive as the normal members.

To discuss them with any definiteness, however, it is necessary to postulate the modes by which they came into being. These should reveal why they are aberrant, though products of the same

[1] See pp. 481–87 of previous article, this *Journal*, Vol. XXVIII (1920).

dynamics as the normal elements. I venture, therefore, to offer three hypothetical, but mutually consistent, ways in which meteors, meteorites, and comets may have arisen naturally and inevitably out of the dynamical system that gave rise to the planets as its normal product.

The problem of the meteors, meteorites, and comets is regarded as essentially one. Though complete demonstration has perhaps not yet been reached, it is assumed that meteors, meteorites, and comets are not only close of kin dynamically, but in some sense mutual derivatives. The spectacular phenomena which seem to put comets in a class by themselves are here supposed to be mainly the effects of the strongly contrasted conditions to which they are subjected at the extremes of their very elongated orbits. It is a suggestive fact that those comets which are supposed to have been reduced from extremely elongated orbits to shorter ones by the action of the great planets, show a notable tendency to lose their spectacular features and finally to pass by disintegration into meteor swarms. In the case of typical comets of extremely elongated orbits, a small loosely organized head—apparently a cluster of still smaller bodies held together by rather feeble gravitative control—swings from a relatively hot perihelion close to the sun to a very cold aphelion far out in space. During its long outer journey, all the constituents must become intensely cold to great depths and be liable to be deeply riven by shrinkage cracks, which, besides leading to coarse fragmentation, should facilitate the adsorption of molecules belonging to the sun's ultra-atmosphere. The action is supposed to be the same as that which gives to meteorites their occluded or combined gases. The outward swing of the comet occupies many years and often centuries, and there is time for even a very attenuated source of supply to furnish the requisite amount of gas-producing material.

When later the comet head, thus charged, approaches the sun, the gases are supposed to be set free by the solar heat on the sunward side, and to be driven forth toward the sun. At the same time, this differential heating is supposed to give rise to rapid and rather violent exfoliation, hurling the dissevered chips to

considerable distances against the feeble gravity of the head. By collisions in the course of their flights, these develop a quasi-gaseous meteoritic swarm whose triturative action should give rise to products of dustlike fineness. Both of these processes would doubtless be attended by much electrical dissociation in which the negative electrons would escape and the positive remain attached, so that electric repulsion would tend to drive both gases and dust sunward until repellant action from the sun reversed the movement and drove the whole backward in the form of the comet's tail. This sketch is very inadequate, but it may serve to suggest ways in which the distinctive features of comets may arise. The nuclei of the comets' heads may be merely clouds or clustered groups of meteorite-like masses loosely assembled by their own feeble attractions, and so subject to easy deployment and reassemblage as conditions require.

If the spectacular features of comets may thus be reduced to the incidental effects of extremely elongated orbits, the way is cleared for explaining how the material of the meteors, meteorites, and comet-heads may have originated, how their highly elliptical orbits were given them, and why these orbits lie in all azimuths and the bodies in them revolve indifferently in forward and retrograde directions in contrast to the systematic, orderly, and concurrent habits of the planetary bodies.

1. The first hypothesis assumes that, previous to the genesis of the present planetary system, the sun had a system of secondaries of the type which it could generate *without the co-operation of any outside body*. The assigned principles of such generation are those rigorous deductions from the kinetic theory of gases on which orbital ultra-atmospheres are postulated.[1] This class of secondaries would be, in the nature of the case, of a very much smaller order than our present planets. The orbits of such bodies would be likely to be thrown into erratic courses by the near approach of the massive body to which the origin of our present planetary system is assigned. Such of these small bodies as were thrown into very long elliptical orbits were made to suffer great extremes of heat and cold and might thus, it is postulated, have taken on

[1] "Celestial Kinships," *The Origin of the Earth* (1916), pp. 101–2.

cometic features, for a time, and later suffered dispersion into meteors and meteorites.

If any of these ancestral secondaries had attained a notable size and happened to be disturbed so as to be drawn through the Roche limit of the sun, it might be disrupted and become a clustered group suited to serve as the nucleus of a comet. This, however, would not be likely to occur in many cases, and so appeal is made chiefly to the riving action of cold in the aphelion journey as the dependable cause for the disrupted character of the comets' heads, and the fragmental features which meteorites commonly show.

2. The second hypothesis assumes that forces of the kinds disclosed by the observations of Pettit on the solar prominences of May 29 and July 15, 1919,[1] projected solar gases and precipitates into the outer regions of the sun's sphere of control, where its attraction was feeble, and where the attractions of neighboring stars and star groups were relatively strong. During these outer flights, the pull of some star, group of stars, or other outside source of attraction drew the ejected masses aside from their normal paths sufficiently to cause them to swing by the sun on their return and thus be forced to take highly elliptical orbits. The planes of these orbits and the direction of revolution thus generated would be determined by the various deviating attractions, so that a system formed by a large number of such deviations would be very heterogeneous orbitally. High ellipticity would be a common characteristic. The principles that control aggregation, as previously sketched in this series of papers, would apply to the projected matter in all such cases. In so far as this matter retained self-control, it would assemble by the precipitate-aggregate method into clouds of aggregates, and these would usually be still more closely assembled into loosely organized bodies well suited to function as the nuclei of comet-heads. These would be subject to all the vicissitudes of temperature and of alternate absorption and evolution of gaseous material, sketched above, and so display for a time the spectacular features of comets, and ultimately be disintegrated into meteorites. In so far as the projected solar matter was too highly dispersed for mutual control, it should have passed

[1] *Astrophys. Jour.* (Oct., 1919), pp. 206–19.

directly into meteoritic matter of the minutest type. At present, meteoritic particles, assumed to be of this type, abound in interplanetary space in such prodigious numbers that many millions are picked up daily by the earth. The formation of precipitate aggregates, in the methods previously sketched, seems to furnish an apt explanation of the origin of chondrules and of the other minute integers that so largely make up meteorites. The collisions of these little bodies as they were entering into the formation of larger bodies, seem well fitted to account for the intimate brecciation, the minute specks of glass, suddenly cooled liquid drops, as well as the strange mixtures of stony and metallic matter, and other distinctive features of meteorites.

3. The third hypothesis is dependent on the pre-existence of the present planetary system. It supposes that the ejected solar matter passed so near some one of the more massive planets that it was thrown into an elliptical orbit in a way similar to the preceding and with similar results. A certain portion of the particles so diverted would take orbits of the planetary type, so far as their planes are concerned, but only a part of these would have a planetoidal degree of circularity. Other portions would have orbits whose eccentricities, orbital planes, and directions of revolution were as various as are those of meteorites and comets. Certain comets are known to have orbits definitely related to the giant planets. This relation is commonly interpreted as the result of reduction from larger and more eccentric orbits by the planet's influence. Without questioning the validity of this interpretation, it is not inconsistent to hold that in a part of such cases, the comets arose *de novo* from planetary action in the way here suggested. Most comets developed in this way would probably belong to the feebly developed evanescent type.

These three hypotheses are entirely consistent with one another and may all be true. They have the merit of being made to rest on the same dynamic basis as the planetary system itself. These hypotheses for the aberrant factors, when added to the planetesimal hypothesis for the normal factors, give a theoretical unity to the whole solar system.

Now, if these are the true lines of interpretation, *the masses of meteors and meteorites, and their methods of infall, throw a flood of light on the sizes and the modes of infall of the planetesimals, for, by this interpretation, they are bodies of like origin and like general conditions.* On a conservative estimate, there are 100,000,000 or more minute meteorites, so small as to be wholly dissipated in the upper air, for every one that is massive enough to remain a visible body until it reaches the earth. Of the latter, none are known to exceed a dozen feet in mean diameter. No meteorite has ever been seen to produce melted soil or rock by its impact. When collisions with bodies that have no atmosphere take place, local melting probably results. The glassy bodies common in meteorites may very likely be such products. But the retention of such heterogeneous structures as are common in meteorites implies that there has been no *general* liquefaction. In so far, therefore, as the testimony of the aberrant factors bears on the size, rate of infall, and liquefying power of their dynamic relatives, the planetesimals, it supports the view that these are small, and in other respects it is in close accord with the deductions hereinbefore drawn from dynamical considerations. It is in intimate harmony with the testimony of the normal factors of the system.

Professor F. R. Moulton and Dr. W. D. MacMillan have been kind enough to read the manuscript of this and the three previous articles (X, XI, and XII), and to make valuable suggestions and criticisms. They are not responsible, however, for the computations. These have been verified by Miss Daisy W. Heath.

A PLEISTOCENE PENEPLAIN IN THE COASTAL PLAIN

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The Black Belt of Alabama is famous throughout the state, and in the surrounding states, for its great fertility, its production of cotton and corn, the levelness of its plantations, the large proportion of negroes to whites, and its numerous ante-bellum mansions—the visible manifestations of its former wealth.

As one rides over the gently undulating surface of the region, with its deep black soil, and crosses the steep-sided gullies and the bluff-bordered rivers, he is impressed with the aspect of topographic youth. However, a more careful study in the field and of the geological literature forces one to the conclusion that the region is not in the youthful stage of a first cycle of erosion, nor in a mature stage of erosion, but that the surface is a recently raised plain, so flat as almost to make the term peneplain—almost a plain—inappropriate. The following excellent description will assist one in visualizing the region:

> The surface of the country, underlaid by the Rotten Limestone, is but little diversified; it is, however, occasionally broken into rounded bald knolls, as may be seen between Arcola and Demopolis, and between Livingston and Sumterville. The summits of these hillocks are sometimes ornamented with cedars, but more frequently they are quite bare, or covered with but a scanty vegetation; even where the surface is but slightly undulating, bald spots occur where the naked rock has come up. But the most remarkable feature of this region is the extensive tracts of land covered with a deep, black soil of great depth and extraordinary fertility, which may be seen in various parts of Sumter, Greene, Marengo, Perry, and Dallas, but more particularly in the "cane brake." The surface of these remarkable tracts has barely sufficient inclination to admit of easy drainage, without giving the water force enough to remove the soil, so that, instead of excavating a channel at the bottom of the trough-like depressions where this sort of land occurs, it is absorbed by the soil, or spreads over a considerable space, where it loses all transporting power.

The unbroken surface of this region is due to the homogeneous character of the limestone, which suffers waste equally on this account, over considerable areas; and hence the entire absence of ravines, and other abrupt irregularities. . . . . In the uncleared parts of the cane brake, ... one can scarcely satisfy himself that he is not standing on the low grounds of a river; the deep, alluvial-looking soil beneath his feet, the moisture-loving long moss (Tillandsia usneoides) above his head, together with an undergrowth of Sabals, Palmettoes, and other natives of damp soils, strengthen the illusion.[1]

Professor Eugene A. Smith's accurate and suggestive description is as follows:

The Selma chalk underlies a belt entering the State from Mississippi and extending eastward with an average width of 20 to 25 miles, to a short distance beyond Montgomery, where its distinctive characters are lost or merged into those of the "blue-marl region." . . . . The somewhat uniform composition of the Selma chalk has caused it to be more deeply and evenly wasted by erosion and solution than the more sandy formations north and south of it. As a consequence, its outcrop is in the shape of a trough, with a gently undulating, almost unbroken surface except where remnants of the once continuous Lafayette mantle have protected the underlying limestone from erosion and have thus formed knobs and ridges capped with its loams and pebbles.

In this belt, more than in any other of the Coastal Plain, the soils show their residuary character. They are, as a rule, highly calcareous clays and, where much mixed with organic matters, of black color. Throughout this section are areas originally destitute of trees and hence known as "prairies." From the agricultural point of view, the Selma chalk or black belt is the most highly favored part of the State and, apart from the cities, holds the densest population.[2]

R. M. Harper[3] characterizes the topography as "gently undulating in a manner difficult to describe, though probably due almost wholly to normal erosion processes," and points out that "some of the region, mostly remote from the rivers, is so level that the railroads have built straight tangents (i.e., straight tracks) a dozen or more miles in length." He also points out the rarity of swamps. The region is traversed by rivers that are, in most places, bordered by steep, bare bluffs—in some places 60 feet

[1] *Tuomey's Second Biennial Report*, pp. 134–37, 1848, quoted by Eugene A. Smith in his report on the *Geology of the Coastal Plain of Alabama* (1894), pp. 282–84.

[2] *Underground Water Resources of Alabama* (1907), p. 13.

[3] Roland M. Harper, "Economic Botany of Alabama," *Geographical Report on Forests*, Monograph 8, Part 1, 1913.

high—of chalky limestone, and the tributary streams have all the characteristics of youth.

The sides of the Black Belt trough are bounded on the north and south by ridges, formed of the more resistant strata of the Coastal Plain, which rise 200 to 300 feet above the general level of the surface. The pronounced cuesta which forms the southern border of the trough is composed of the sandy, more resistant Ripley (Cretaceous) sediments.

The Black Belt, Black Prairie, Cotton Belt, or Cane Brake, as it has been variously called, can be briefly described as a belt of rich, black soil with an average width of 20 to 25 miles, and an area in Alabama of about 4,300 square miles. It extends in an east-west direction in south central Alabama and conforms exactly with an easily decomposed, impure, chalky limestone of rather uniform composition (Selma chalk) which has a thickness of about 1,000 feet in the western part of the state and thins out and disappears in the east near Montgomery. This formation dips to the south at the rate of 30 to 40 feet to the mile while the surface slopes at a much less rapid rate in the same direction. It is the weathering of the beveled edges of this limestone that determines the width and position of the Black Belt. The soil formed from this rock is a clay of exceptional fertility but somewhat difficult to cultivate because it bakes in summer and becomes tenacious mud in winter.

After the deposition of the Coastal Plain sediments a deposit of red sandy loam, called the Lafayette formation, was laid down on them, either during the early Pleistocene or near the close of the Pliocene, and formed a veritable mantle covering many hundreds of square miles. The depth of this formation is, in places, as much as fifty feet, but little of it has a thickness of more than 25 feet. The origin of the Lafayette has given rise to much discussion,[1] but as the underlying formations in Alabama contain little quartz from which pebbles could be made, the abundant water-worn quartz pebbles show that in this state, at least, it must have been transported long distances. On the sides of the Black Belt trough some knobs and ridges are capped by this deposit, proving

[1] W. W. Shaw, *U.S. Prof. Paper 108 H.*

that the Black Belt was once covered with it. The almost complete absence of the Lafayette over the area underlain by the Selma chalk and its presence on other parts of the Coastal Plain north and south is attributable to the greater ease with which the chalk is weathered and eroded. Because of its solubility and lack of strength, the streams that flow through the limestone quickly cut their beds to grade. In other parts of the Coastal Plain which are underlain by limestone, it is also found that very little remains of the once widespread cover of Lafayette.

The features which lead to the belief that the Black Belt of Alabama is in the youthful stage of a first cycle of erosion was based upon the facts (1) that its surface is so level in certain areas as to give it an appearance of topographic youth; (2) that the rivers are bordered by steep banks or bluffs and are in a youthful stage of an erosion cycle.

The evidences which indicate that the region was peneplained and has been elevated in comparatively recent times are: (1) that it occupies a troughlike depression 200 to 300 feet lower than the bordering lands to the north and south; (2) that, although the soil is a clay, and is consequently very favorable for the retention of water, swamps are nevertheless uncommon except in river bottoms, showing that the drainage had been thoroughly established; (3) that the Lafayette, which once covered the Black Belt, has been almost entirely removed from it; (4) that the thick, residual soils of the region were probably formed chiefly after the land was reduced to a peneplain (at the present time they are being rapidly eroded away); (5) that the present youthful appearance of the region is due to a comparatively recent elevation of the peneplain 60 or more feet, which permitted the rivers to sink their beds; (6) that the peneplanation must have taken place during the Pleistocene, as is shown by the fact that the region was reduced to a nearly level surface and that a thick residual soil was formed after the removal of the Lafayette, a formation that was deposited not earlier than late Pliocene and, more probably, during the Pleistocene.

Estimates of the length of geological time are so uncertain that little dependence can be placed on them, but it is, nevertheless,

interesting to speculate upon the time required for the removal of the Lafayette loams, sands, and gravels from the Black Belt and for the reduction of the surface during part of the Pleistocene. Penck's estimate of 500,000 to 1,000,000 years for the duration of the Pleistocene, based upon the rate of advance and retreat of the Pleistocene Ice Sheets, is to be contrasted with Barrell's[1] minimum estimate of 1,500,000 years based upon a study of radioactivity. A few years ago Barrell's estimate would have seemed extravagant, but when one considers that a region, such as the one under discussion, has been denuded of a thick deposit of gravel and loam, has been reduced to a peneplain, has been weathered so long as to form a thick residual soil, has been raised, and, finally, has been so dissected by streams as to make a topography of youthful aspect, the larger estimate does not seem impossible.

In 1906, Chamberlin and Salisbury[2] presented figures as to the duration of time since the Kansan glacial epoch, giving 300,000 as a likely minimum, and 1,020,000 as a likely maximum. Had the statement covered the time since the beginning of the Pleistocene, these figures would have been considerably larger.

The physiographic history of the Coastal Plain of the Gulf of Mexico has not as yet been carefully worked out, and it is probable that a thorough study will show that this surface instead of being the youthful topography of a first cycle of erosion, is, for the most part, the incised surface of a peneplain or a plain of marine abrasion, in which are subordinate peneplains such as that of the Black Belt. The unconsolidated sediments and broad intervales give the impression of youth but the beveled edges of the formations which underlie the Coastal Plain and the level, outstanding cuesta ridges are suggestive of peneplanation. The writer hopes to be able to make a further study of the physiographic history of our Gulf Coastal Plain and with it a study of the Atlantic Coastal Plain.

[1] J. Barrell, "Measurements of Geological Time," *Geological Society of America Bulletin*, Vol. XXVIII (1917), p. 892.

[2] *Earth History*, Vol. III, p. 420.

THE MECHANICAL INTERPRETATION OF JOINTS[1]

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PART I

OUTLINE

I. THE JOINTS OF MINE FORK

In the course of field work in eastern Kentucky, in 1917, the writer observed a case of local jointing which gave him the clue to the following investigation.

On Mine Fork, a few hundred yards above the mouth of Lacy Creek, in Magoffin County, close to the Morgan and Johnson county lines, in a nearly vertical cliff of a strongly cross-bedded, coarse-grained sandstone forming the top of the Lee Group of the Pottsville series, the system of intersecting joints shown in the accompanying sketch (Fig. 1) is exposed along the roadside. Unfortunately the commercial work in which the writer was engaged at that time did not permit him to spend any more time in that vicinity than was necessary for a hasty survey of this exposure.

[1] Part I of this paper was presented, in essence, at the last meeting of Section "E" of the American Association for Advancement of Science, at St. Louis, December, 1919.

It was found that (*a*) The jointing is confined to the upper third (or even less) of the massive sandstone which is here about 100 feet thick. It is entirely lacking below. (*b*) It marks the crest of a minor anticline on the downthrow side of a conspicuous fault. (*c*) The average hade of the joint-traces on the practically vertical exposure which trends about in a NNE–SSW direction, is: set I: 27°—NNE; set II: 35°—SSW; inclosed angle: 62°. (*d*) The average strike of the joint-traces, measured on the horizontal surface of projecting ledges, is: set I: N 78 W; set II: N 27 W; inclosed angle: 51°. (*e*) The joints of set I are much better developed,

FIG. 1.—Jointing in vertical cliff of massive, cross-bedded sandstone on Mine Fork, Magoffin County, Kentucky.

longer, more continuous and more regular in their course than those of set II, both in the vertical and in the horizontal planes.

For two reasons the occurrence of this system of joints at this locality seemed surprising. There could be little doubt that these joints represented planes of shearing. The writer had, however, always associated the fracturing of hard materials by shearing with compressive stresses or, at best, with compound stresses resulting in torsion. But here he was dealing with a clear case of simple tension along the crest of an anticline, causing a hard sandstone to fail along typical planes of shearing.

He had also been accustomed to ascribe to the planes of maximum shear a general tendency to intersect at right angles. No

such tendency could be inferred from these joints, which intersect uniformly at an angle close to 60°, with the obtuse angle facing in the direction of the tensile stress.

II. HARTMANN'S LAW

Following the clue given by these observations, the author became acquainted with a book published in 1896 in Paris by L. Hartmann under the title *Distribution des déformations dans les métaux soumis á des efforts*,[1] containing a wealth of experimental data and a fascinating discussion of the lines forming on the surfaces of metals when strained beyond the elastic limit, known as Lüders' lines.[2]

When a highly polished plate of metal is subjected to a very gradually increasing simple tensile stress, the first permanent deformation is accompanied by the sudden appearance of one or several delicate straight lines or bands cutting in an oblique direction across its surface. Suitable illumination shows them to be depressions. When the stress is further increased, the existing lines widen and new ones appear, forming two conjugate systems of oblique lines, symmetrical to the direction of maximum stress and intersecting at a constant angle which in most metals (and rocks) is greater than 90°.[3] This angle remains unchanged with growing tension and is thus independent of the intensity of the stress. The final rupturing may entirely or partly follow these lines or cut across them at right angles to the tension.

Under compression, similar systems of lines form, but now the angle of intersection bisected by the direction of the compressive stress, for most rocks and metals, is smaller than 90°, and for the same material is the supplement of the one obtained under tension.

[1] Berger-Levrault, Paris, 1896.

[2] Called after Lüders of Magdeburg who first described them fully in 1860. "Über die Äusserung der Elastizität an stahlartigen Eisenstäben und über eine beim Biegen solcher Stäbe beobachtete Molekularbewegung," *Dingler's Polytech. Jour.*, Vol. CLV (1860), p. 18 (not seen).

[3] Ten good illustrations of strips of low steel showing yield lines developed under tensile stress, are given in H. Marten's *Handbook of Testing Materials* (translated by Gus. C. Henning), John Wiley & Sons, N.Y., 1899, Vol. I, Pl. 1, Figs. 3, 5, 12, 14–20.

The lines in this case are depressions only on one side, with the corresponding lines on the reverse side forming delicate ridges. Final rupturing, under compression, always follows these lines.

The great importance of these lines of Lüders for our purposes lies in the fact that they represent the outcrops of internal planes of yielding, differing largely in scale and degree of deformation, not in origin, from the planes of shearing observed on a large scale in nature.

In fact, in the small test piece as on a gigantic scale in nature, we see that the stress acts not uniformly on every unit of the mass undergoing deformation, but that it reaches a maximum along these geometrically distributed surfaces, while maintaining lower values in the volume between. We seem to be dealing here with a sharply defined application of the principle of least work.[1] At every point along every imaginary line of stress within a body undergoing elastic deformation there exists the tendency to shear in any one of an infinite number of directions all inclined to the direction of stress at the same angle, the sum of which forms two infinitely small cones joined by their apices.[2] Out of the infinite number of surfaces which may be obtained by connecting any two of such adjoining possible directions of shearing, those only will form which involve the expenditure of a minimum of energy.

When the lines of stress are not parallel, owing to the unequal distribution of stresses, the resulting surfaces of yielding may be very complex and the pattern of lines formed by their traces on the surface may be far from regular (Fig. 2*A*–*C*[3]).

In such cases Lüders' lines can be used to reconstruct the lines of maximum stress on any given test piece, by drawing the lines bisecting the angle of shear at every point of intersection of the shearing planes. Figure 2*C* represents the lines of stress derived in that way from Lüders' lines as obtained in the experiment illustrated in Figure 2*A* and *B*.

[1] H. von Helmholtz, "Über die physikalische Bedeutung des Princips der kleinsten Wirkung," *Wissenschaftliche Abhandlungen*, Vol. III, pp. 209–10.

[2] L. Hartmann, *op. cit.*, pp. 18–19.

[3] Hartman, *loc. cit.*, Figs. 48–50.

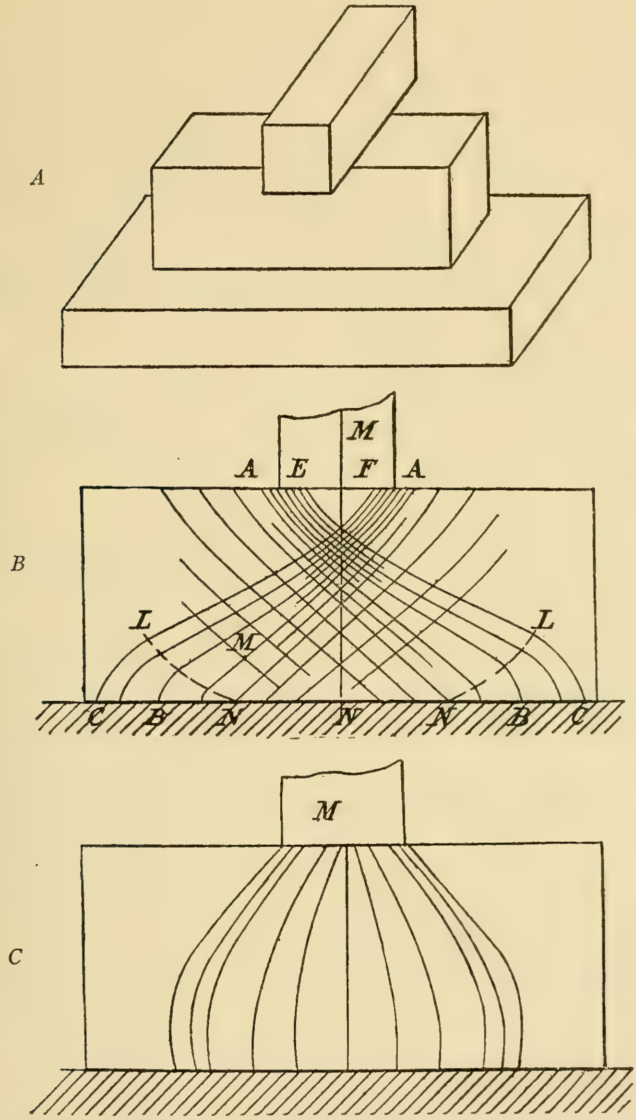


FIG. 2.—*A*. Arrangement used in one of Hartmann's experiments in which the test piece (in the center) was subjected to uniform compression over its whole base, while the upper surface suffered compression in the center only. (L. Hartmann, 1896.) *B*. Lüders' lines produced in the experiment illustrated in Fig. 2*A*. (L. Hartmann, 1896.) *C*. The theoretical lines of stress (bisecting the angles of Lüders' lines) reconstructed on the test piece illustrated in Fig. 2*B*. (L. Hartmann, 1896.)

The most irregular pattern of Lüders' lines results when the lines of stress are not parallel to the axis of the test piece, but intersect with it at varying angles. In that case, the angle formed by planes of yielding may be cut by the surface in all possible directions and the apparent angle of intersection of Lüders' lines as seen on the surface varies from point to point and must not be mistaken for the true constant angle bisected by the line of maximum stress of which it is only the oblique outcrop.

In 1900, O. Mohr published a mathematical study which led him to views practically identical with those of Hartmann. They may be summarized as follows:[1]

a) In all hard materials (except the most brittle ones), under tensional as well as compressional stresses, deformation by shearing takes place in two systems of intersecting planes of shearing.

b) Adjoining planes of one system are parallel.

c) The angle at which the two systems intersect is constant for any given material, that is, it is independent of the nature or intensity of the stresses involved.

d) For the same kind of material, this angle differs the more from 90° the harder and the more brittle the material is (e.g., hard or soft steel).

e) If we consider tension as negative compression, the law governing the arrangement of the yield planes with reference to the principal axes of stress which will be referred to as *Hartmann's Law*, can be expressed as follows: In brittle materials, *the acute angle formed by the shearing planes is bisected by the axis of maximum compression*, and *the obtuse angle by the axis of minimum compression which is generally negative, representing tension.*

f) If the position of the principal axes changes from point to point, the shearing surfaces are warped. The less this is the case, i.e., the more nearly homogeneous a material is, the more regular are the shearing planes.

g) The shearing planes do not originate simultaneously, and are not uniformly distributed.

[1] F. Rinne, "Vergleichende Untersuchungen über die Methoden zur Bestimmung der Druckfestigkeit von Gesteinen," *N. Jahrb. f. Min.*, etc., Vol. I (1907), p. 45.

III. HARTMANN'S LAW APPLIED TO EXPERIMENTAL AND FIELD OBSERVATIONS

Hartmann's law enables the geologist as well as the mechanical engineer to reconstruct the position of the principal axes of stress in any given body subject to mechanical deformation—be it a test specimen in the laboratory or the exposed portion of a fractured rock-mass—by analyzing from point to point the position of the planes of shearing. The direction bisecting the acute angle formed by the planes of shearing corresponds to that of the greatest principal axis of compressive stress, while the bisectrix of the obtuse angle gives the direction of the least stress, which in most cases represents active tensile stress. The direction of the intermediate principal stress coincides with the line of intersection of the two planes of shearing.

It is essential, however, to realize at the start the limitations of this law.

a) It applies only to brittle substances.

b) Not all lines of fracture are lines of shearing. Brittle materials, such as cast iron or hard steel, and most rocks under simple tension habitually fail along planes of fracture at right angles to the direction of maximum tensile stress.[1] Soft steel, on the other hand, fails along inclined planes of shearing under tension as well as under compression.

c) The position of the planes must be studied in space, not in any accidental plane of exposure.

d) The principal stresses inferred from them need not be identical with any real stresses, but may be only the resultants of the combined action of several stresses ("equivalent" stresses).

We may now proceed to test the usefulness of Hartmann's law by applying it to a few selected experimental data and geological field observations.

1. *Compressive stress vertical, tensile stress horizontal.—a*) When a cylindrical test piece is subjected to compression beyond the elastic limit, Lüders' lines make their appearance on its surface, forming a characteristic pattern of symmetrical intersecting spiral

[1] See, for instance, A. L. Jenkins, "Combined Stresses," *Jour. Amer. Soc. Mech. Engineers* (1917), p. 696.

lines, with the acute angles formed by their intersection facing the direction of pressure. On specimens of Carrara marble used by Rinne[1] this angle measured 60°, on those used by Kármán[2] it measured 54°, while red sandstone (*Buntsandstein*) gave a value as low as 38°.

When the pressure is increased until rupture occurs, the plane of fracture forms a symmetrical cone with an apical angle equaling the angle of shear characteristic of the material. In this case, the least principal stress equals the intermediate stress. Thereby its position is made indefinite with reference to the infinite number of directions in the plane common to the two lesser stresses, normal to the greatest principal stress. The peculiar conical fracture is the result.[3]

As soon, however, as any one of the infinite number of possible directions in the plane normal to the greatest stress offers a minimum of resistance, rupture occurs[4] along two well-defined planes, as indicated in Figure 3. Daubrée's classical experiments on blocks made of a mixture of plaster of Paris and beeswax[5] correspond directly to this case.

[1] F. Rinne, "Vergleichende Untersuchungen über die Methoden zur Bestimmung der Druckfestigkeit von Gesteinen," *Neues Jahrb. f. Miner.*, etc., Vol. I (1907), p.45.

[2] Th. von Kármán, "Festigkeitsversuche unter allseitigem Druck," *Zeitschr. d. Vereins deutscher Ingenieure*, Vol. LV (1911), pp. 1748–57.

[3] The remarkable fracturing in the form of parallel and interpenetrating cones observed in the brittle white limestones of the Upper Jurassic along the intensely shattered margin of the crypto-volcanic basin of Steinheim seems to be due to this condition. W. Branco u. E. Fraas, "Das kryptovulkanische Becken von Steinheim," *Phys. Abhandl. d. K. Preuss. Akad. d. Wissensch.* (Berlin, 1905), pp. 36–38.

[4] In a cube where four directions offer an identical minimum of resistance, the planes of fracture form a pyramid as may be seen in any ordinary crushing test.

[5] A. Daubrée, "Études synthétiques de géologie expérimentale" (Paris, 1879), pp. 315 ff. and Figs. 93 and 94. For a copy of Fig. 93 see, e.g., Van Hise, "Principles of North American Pre-Cambrian Geology," *Sixteenth Ann. Rep. U.S.G.S.* (1895), Pt. I, p. 644, Fig. 126. Note in this figure the difference between Lüders' lines and the final plane of shearing. The former, marked "R," do not, at first, correspond to continuous internal surfaces. They represent purely local effects along individual lines of stress. The establishment of large planes of shearing (marked "F") is a later development. The difference between the two is shown strikingly on the right side of the block, where the main fracture cuts diagonally across Lüders' lines. This contrast between Lüders' lines and the final planes of rupture is met with in all experiments. It seems to indicate that at first the greatest tension exists parallel to the surface of the test specimen, due to the stretching of the horizontal dimensions accompanying the vertical shortening. Rupture, on the other hand, gives dominance to the direction of easiest movement in a radial direction.

b) It is easy to see that the joints on Mine Fork, Kentucky, described in the introduction to this paper, correspond to this type. Here, however, the active stress was the horizontal tension existing at the top of the anticline, while the weight of the overlying rock-masses, giving the compressive stress, was merely passive.

The analysis of joints can, however, be carried farther and may often yield information of decisive value to the field geologist.

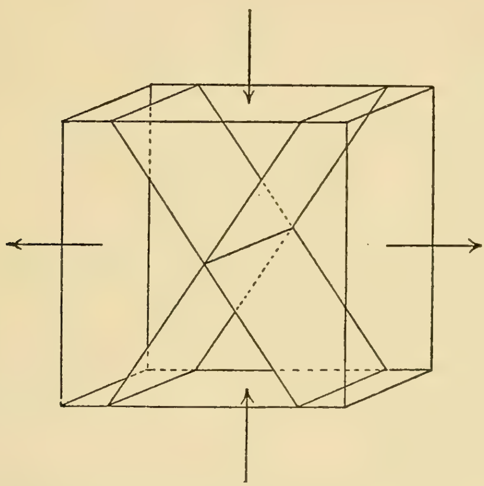


FIG. 3.—Diagram illustrating the position of the planes of shearing in a brittle body subjected simultaneously to vertical compression and horitonzal tension.

A detailed analysis of the joints on Mine Fork will be given here to illustrate the method of analysis used by the writer.

The exposure on Mine Fork is such as not to give the true dip of either of the joint planes. The joints themselves are filled with mineral matter and their surface is nowhere exposed. But their apparent hade was measured on the vertical face of the exposure trending essentially NNE—SSW and their strike was determined on the level top of the cliff.

	Set I	Set II
Apparent hade:	27° northward	35° southward
Strike:	N 78 W	N 27 W

A complete analysis from these data involves the following steps. Find

1. The actual position of the two planes in space.

2. The direction, in space, of the line of intersection of the two planes which corresponds to the position of the intermediate principal stress.

3. The position of the plane normal to this line.

4. The location in this plane of the other two principal stresses bisecting the acute and obtuse angles respectively.

The stereographic projection is admirably adapted to the demands of problems of this kind. By its use, the position of the principal stresses in space can be obtained in the field from any given set of joints within a few minutes. In the following brief description of the construction of Figure 4, a working knowledge of the stereographic projection is assumed.[1]

1. Draw the line *Ex-Ex*, trending N 23 E, to represent the vertical plane of the exposure. On it, mark the point c, 27° southward from O, and c', 35° northward from O. The planes acb and $a'c'b'$ represent the two joint planes and can now be drawn.

2. Since the two points O and d are common to both planes, Od is the line of intersection of the two planes, that is, the direction of the intermediate stress.

3. On the great circle acb mark point e, and similarly point e' on $a'c'b'$, both 90° from d. Through e and e' draw the great circle $fee'g$, representing the plane normal to Od. On it we can read directly the true value of the acute angle of the shearing planes, which in this case is 72°.

[1] For a detailed discussion of the stereographic projection see A. Johannsen, *Manual of Petrographic Methods*, p. 17. McGraw-Hill Book Co., 1914. For most purposes a protractor giving great circles and vertical small circles 10° apart, such as is given (after Penfield) in A. F. Rogers, *Introduction to the Study of Minerals* (McGraw-Hill Book Co., N.Y., 1912, pp. 82–86), is perfectly sufficient. It can readily be copied and carried in the notebook for use in the field. Greater accuracy can, of course, be obtained by the use of Wulff's net, a large copy of which is contained in E. E. Wright, "The Methods of Petrographic-Microscopic Research," *Carnegie Inst. Pub. 158*, Pl. III.

The reader who has had little practice in the use of the stereographic projection will find it easy to visualize Fig. 4 by remembering that the great circles must be imagined to be drawn on the surface of a hemisphere resting on the circle NESW with O at its center. A line such as dO, therefore, represents a radius extending from the surface of the hemisphere, at d, downward to the center O.

4. Find the point *i*, located halfway between *e* and *e'*. The line *iO*, lying in a plane normal to the intermediate stress *dO*, and in the plane *hidj* bisecting the acute angle of the shearing

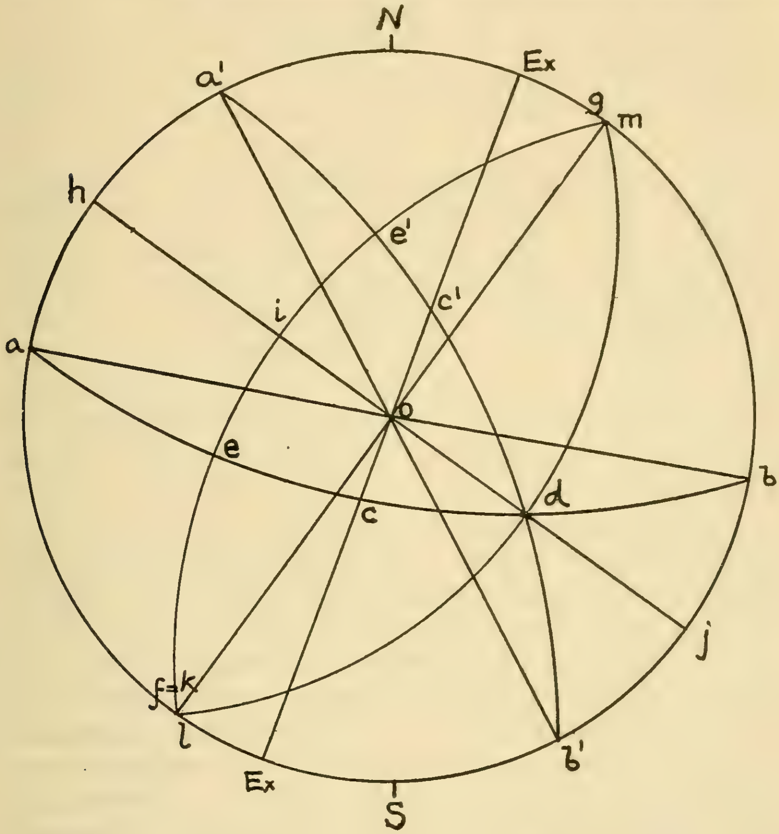


FIG. 4.—Stereographic projection of the joints on Mine Fork, Kentucky. *Ex* = Trend of exposure; *ab* = set I of joints; *a'b'* = set II of joints; *od* = line of intersection of joint planes = position of intermediate principal stress; *hidj* = plane bisecting the acute angle of the joint planes; *oi* = located in this plane, normal to *od* = position of the greatest (compressive) principal stress; *mdl* = plane bisecting the obtuse angle of the joint *hid* planes; *og* = located in the plane *mdl*, normal to *od* = least (tensile) principal stress; *mdl*, *gif* = principal planes.

planes, represents the direction in space of the compressive stress. The line *hj* gives the trend of this stress in a horizontal plane.

5. 90° from *i*, on the great circle *gif*, mark the point *k*, which in this case practically coincides with *f*. The line *kO*, lying in

the plane normal to *Od* and 90° from *Oi*, represents the direction in space of the tensile stress, and the line *ml*, in the vertical plane *lkdm*, gives the horizontal trend of this stress.

This analysis leads to the following conclusions:

The direction of *Ok*, of the tensile stress, differs only 3° from the horizontal, as would be expected at the crest of an anticlinal bulge.

The pull was slightly inclined downward in the direction N 33 E.

The very crest of the anticline, therefore, must be sought on the left side of the exposure, a short distance to the southwest. The differential movement which develops when strata slip past each other in the process of folding was here directed toward the crest and favored the development of the joints of set I which are more numerous, more regular, and stronger than those of set II.

The direction N 33 E of the greatest tension suggests in a general way the dip, and therewith also the strike, of the strongly cross-bedded sandstone.

2. *Both, compressive and tensile stresses horizontal.—a*) When Daubrée subjected to torsion narrow strips of glass, measuring about a yard in length, and produced on them the well-known system of intersecting fractures, he gave the science of geology one of its most impressive laboratory experiments and one of its most popular textbook illustrations on the subject of joints.

Careful analysis, however, reveals the fact that the conjugate systems of fractures which he produced, do not correspond directly to similar joint systems in nature. Figure 5 is a sketch of the fractures forming two prominent "fans" on one of Daubrée's plates.[1]

The tendency to form such "fans" is obvious in all torsion experiments made with glass. Duparc and LeRoyer found that it is the more pronounced, the thicker the glass plate is which is used for the experiment.[2]

[1] The one in the center of the plate reproduced on Plate XII of Haug, *Géologie*, Vol. I (Paris, 1911) (opp. p. 228).

[2] L. Duparc and A. LeRoyer, Contributions à l'étude expérimentale des diaclases produites par torsion," *Archives des Sciences phys. et nat.*, 3me sér. XXII (Genéve, 1889), p. 307. Daubrée used plates 7 mm. thick; on plates of 2 mm. thickness or less, "fans" may not form at all.

Each "fan" consists of a gently curved "master-joint," marked t and t', from which start, at a very acute angle, a number of minor joints, s and s', which unmistakably tend to be straight and parallel to each other.

The clue to this peculiar fan-structure of fractures we find in Hartmann's experiments with rectangular strips of soft steel.[1] Under torsion, two systems of Lüders' lines appeared on them, each parallel to one of the sides of the test piece, intersecting practically at right angles. This indicates that the direction of greatest tension traverses the surface obliquely, forming an angle near 45° with the axis of torsion.[2] When the deformation was carried farther additional lines of deformation appeared in the vicinity of the longer edges, bisecting the angles formed by the first set of lines.

When a plate is subjected to simple torsion, each element of the upper surface suffers simultaneously tension in one direction and compression at right angles to it. The same is true of the lower surface, but with the directions of tension and compression reversed.[3]

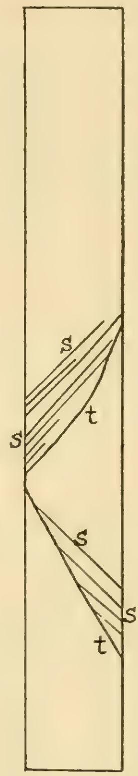


Fig. 5.—The fractures forming two characteristic "fans" on one of the glass plates used in Daubrée's experiments on fractures produced by torsion.

At any point on either surface, therefore, the position of the shearing planes is sharply defined through the combined action of tension and compression as shown diagrammatically in Figure 6. In case tension fractures are formed in addition, they bisect the acute angle of the shearing planes. This is what happened in Hartmann's experiment with

[1] Hartmann, *loc. cit.*, p. 175 and Fig. 173.

[2] This can be verified readily by drawing a circle on the flat side of a rubber eraser and twisting it. G. F. Becker, "The Torsional Theory of Joints," *Trans. Amer. Inst. Mech. Engineers*, Vol. XXIV (1895), p. 136.

[3] For the purposes of the following discussion it is important to remember that essentially horizontal tensional stresses arise in surfaces made convex, and similar compressive stresses in surfaces made concave through the process of bending.

strips of soft steel. The second set of fractures, formed after shearing was well under way along Lüders' lines, consisted of tension fractures, one started from the lower, the other from the upper surface.

Glass, on the other hand, being a highly brittle substance, in contrast to soft steel, will fail along tension fractures rather than along planes of shearing. The fractures marked *t* in Figure 5 are the only ones that form when the glass plate used in the experiment is very thin. They must, therefore, be tension cracks, one set produced on the under side, the other, symmetrical to it, on

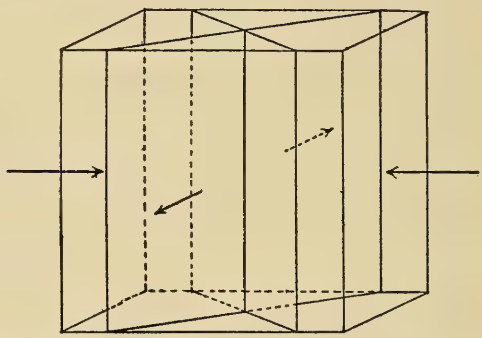


FIG. 6.—Diagram illustrating the position of the planes of shearing in a brittle body subjected simultaneously to compression and tension, both in a horizontal direction.

the upper surface, and both finally extended to both surfaces, owing to the thinness of the plate. The gentle curving of these cracks is quite in harmony with this interpretation.

The other set of fractures, marked *s* in Figure 5, intersects with the tension cracks at angles varying from 15° to 25°. This, however, is one-half of the angle of shearing characteristic of glass.[1]

The same angle for soft steel is approximately 45°. It is evident, therefore, that these fractures represent shearing planes produced by the compressive stress acting in the direction normal to the tensile stress. In the experiments made with glass, however, in contrast to those with mild steel, only one set of the shearing planes forms in connection with a tension crack, that only which

[1] To verify this, it is sufficient to compress small pieces of thick plate glass in a strong vise. The resulting angle of shearing can be measured conveniently by means of Penfield's contact goniometer.

lies favorable to the differential movement resulting from the process of torsion. Here, again, the fractures produced on the upper surface extend down to the lower surface and vice versa.

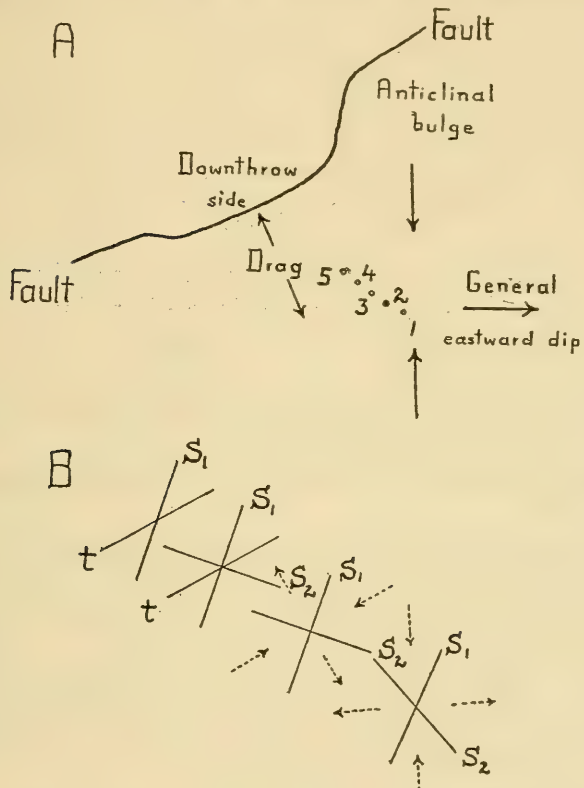


FIG. 7.—*A*. Map sketch, showing relation of stations on Crooked Creek, Adams County, Ohio, at which joints were measured, to the fault and to other structural features. *B*. Diagram showing the position of the joints observed at the stations 1, 2, 3, 4, 5. S_1 S_2=shearing joints; t=tension joints.

Since the intensity of the compressive stress increases with the thickness of the plate, it is evident that the fan-shaped groups of cracks will form the more freely the thicker the plate is.

The most striking feature of Daubrée's famous experiment, therefore, namely the formation of two systems of fractures intersecting approximately at right angles, is an accidental result of the exceptional brittleness of glass and the thinness of the plates

used, permitting the fractures produced on the upper and lower surfaces respectively to interpenetrate.

Most rock materials, on the other hand, are less brittle than glass and therefore more inclined to yield along shearing planes when subjected to torsion. Moreover, at least in the case of the larger joints observed in nature, the thickness of the formations undergoing deformation through torsion is sufficient to keep the fractures formed on the upper and lower surfaces separate.

In general, therefore, joints produced by torsion in the course of larger earth movements should occupy the position indicated in Figure 6 with the direction of both, compressive and tensile stress, not differing much from the horizontal. In addition to these, tension fractures, bisecting the angle of the other joints, may occur and even dominate. These, together with an unequal development of the two sets of shearing joints, with possibly one even missing completely, may give considerable variation to the appearance of the same joint system from point to point.

We may now turn to a discussion of three selected cases of joint systems.

a) In Figure 7*A* the general structural relations are given for five points along Crooked Creek, Adams County, Ohio, at which the position of joints was determined by the writer. The joints here cut in a nearly vertical position through the rather thin and even beds of the fine-grained dolomite of the Bisher formation.

Figure 7*B* shows the strike of these joints as contained in the following field notes.

Station	Set s_1	Set s_2	Set *t*
1.......	N 25 E strongly developed	N 40 W sharp and persistent	....
2.......	N 20 E well developed	N 70 W (average) strong but variable	....
3.......	N 20 E sharp and regular; closely spaced (2–10 in. apart)	N 70 W (average) few and far apart (several feet); irregular.	....
4.......	N 22 E sharp and regular; (1–2 feet apart)	N 70 W very few, only three good joints seen	N 62 E sharp and regular, 1–2 feet apart
5.......	N 20 E sharp and regular	....	N 65 E dominant system, closely spaced

The very regular systems of joints observed at station 1 obviously owe their existence chiefly to the compressive stress caused by the upward buckling of the strata farther north along the fault. The change of the angle of shearing from 65° at station 1, to 90° at stations 2 and 3, probably is due to factors which will be discussed in the second part of this paper. It is brought about by a shifting of the trend of the system s_2 which at the same time becomes more and more irregular and scattered. At station 4 set s_2 is only represented by a few widely separated cracks, while a new system of fractures makes its appearance. They are parallel to the fault and become increasingly prominent and closely spaced as the fault is approached. They must be tension cracks.

The joints at station 5 offer an exact analogy to the fan-shaped cracks formed on the upper surface of a glass plate under torsion, with shearing planes developed only on one side of a tension crack.

The great practical value of such an interpretation of joints, during the progress of field work, is obvious. In this case, for instance, the joints at stations 1 to 3 would lead the field geologist at once to look for an uplift either north or south of these points, or both. The sudden appearance and increasing importance of an additional system such as the joints of set t would suggest the neighborhood of a flexure or a fault not far to the northwest striking N 65 E.

Information such as this will certainly pay for the time spent on detailed intelligent observation.

b) The remarkable jointing exposed along the shores of Lake Cayuga and Lake Seneca, "resembling the gigantic ruins of Cyclopean architecture," has been made classic through the series of woodcuts published by Hall in 1843.[1]

Miss Pearl Sheldon[2] has given us a large number of careful measurements of these joints in the vicinity of Cayuga Lake. Two systems of joints stand out from all others. They are generally stronger, more regular, and remarkably constant in their

[1] *Geology of New York*, Pt. LV (Albany, 1843), pp. 303–6. For good modern illustrations see, e.g., *Watkins Glen-Catatonk Folio*, No. 169 (1909), Pl. I, Figs. 15 and 16; and *Jour. Geol.*, Vol. XX (1912), p. 78.

[2] Pearl Sheldon, "Some Observations and Experiments on Joint Planes," *Jour. Geol.*, Vol. XX (1912), pp. 53–79; 164–83.

trend. They are practically vertical. The strike of the one set ranges from N 70 E to N 80 E with the majority lying between N 75 E to N 78 E. The other set has a strike ranging from N 20 W to N 10 E. Frequently joints of the two extremes, near N 20 W and N 10 E, are present at the same locality.

No detailed data are given for the large number of minor joints of this region. Their trend seems to be highly variable, in general and from point to point, and ranges through all points of the compass. They are often curved and irregular, and as a rule small. They generally show a large hade, ranging as high as 60°.

The remarkably uniform position of the two major joint systems[1] stands in strong contrast to the highly variable dip of the limbs of the low anticlines and synclines formed by the rocks of the region, as shown on the geological map.[2] This contrast is especially striking, as Miss Sheldon points out herself, where the dip and strike of the rocks changes rapidly from point to point along the pitching end of an anticline (for instance, the Shurger Point anticline)[3], while the position of the joint planes remains unchanged.

It is evident, therefore, that the formation of these joint systems was independent of the folding and followed it.

Here, as on Crooked Creek, one system is quite constant in its trend, while the other varies in such a way as to form angles ranging from about 65° to 90° with it. We are, therefore, justified in the assumption that they represent planes of shearing produced by compression in a NE–SW direction under general conditions of torsion. To test this interpretation, we turn to the geological maps of Watkins Glen and Catatonk quadrangles.

West of Cayuga Lake, along the axis of the Watkins anticline, the contact of the Portage and Chemung formations is nearly level, varying between 1,480 and 1,560 feet above sea-level for a distance of over 18 miles. As it approaches the valley of Cayuga Inlet, it rises above 1,600 feet. East of Ithaca, in the same general

[1] See especially Figs. 6 and 7 of Miss Sheldon's paper.

[2] See *Watkins Glen-Catatonk Folio*, No. 169.

[3] *Loc. cit.*, p. 67.

direction, the contact rises rapidly to over 2,100 feet in a similar distance. A closer inspection of the northeast corner of Catatonk Quadrangle reveals the presence of considerable doming in the general direction suggested by the position of the joint planes. This broad anticlinal bulge does not seem to be mentioned in the text of the folio. The fact that the writer's attention was called to it through the analysis of the joints of Cayuga Lake, serves well to illustrate the practical possibilities of the method employed.

The presence of an uplift to the northeast accounts for the existence of a compressive stress in that direction. The horizontal tensile stress implied by the position of the joint planes can be accounted for equally well. Crossing the shores of Cayuga Lake in a southeasterly direction (suggested by the obtuse angle of the joints), we find that, on the crests of the Fir Tree Point, Watkins and Alpine anticlines, the contact of the Portage and Chemung formations remains essentially at an elevation between 1,600 and 1,700 feet above sea-level. Beyond the Alpine anticline, however, in the same southeasterly direction, within a similar distance, the same contact drops to near 1,000 feet in the vicinity of Jenksville in Newark Valley Township.

The existence of this depression in the direction suggested by the position of the joint planes, leaves little doubt that this relatively pronounced flexure gave rise to the tensile stress involved in the formation of the joints.

c) For a last example we turn to Thwaites's paper on the "Sandstones of the Wisconsin Coast of Lake Superior."[1]

When we plot the strike of the joints of this region as recorded in the table on page 96, it appears that the peninsula north of Washburn, including the Apostle Islands, in contrast to the regions to the west and south, is traversed by two dominant and persistent systems of major joints. One of the two strikes on the average E–W, the other about 10° east of north. Most probably they represent planes of shearing. The position of the acute angle points to the action of a compressive stress in a NE–SW direction, with a tensile stress acting in a NW–SE direction.

[1] F. T. Thwaites, "Sandstones of the Wisconsin Coast of Lake Superior," *Wis. Geol. and Nat. Hist. Sur., Bull. 25* (1912).

The map accompanying Thwaites's paper shows that the jointed area lies in the continuation of the northeastern end of the great Douglas thrust fault. If this fault had any horizontal component in the northeasterly direction, it could have supplied the compressive stress responsible for the position of the joints.

Unfortunately, the fault contact of the Middle Keweenawan traps with the underlying much younger Orienta sandstone was found exposed only at four localities. At three of these, the exposures were not even found sufficient to measure the hade of the thrust plane.[1]

In the vicinity of the falls of the Amnicon River, however, the fault-plane proper was found exposed at two separate localities, about 500 feet apart. Here, at both points, two systems of grooves were observed on slickensided surfaces in the immediate vicinity of the fault, on surfaces of conglomeratic beds of sandstone which represent most probably shreds of lower beds dragged up along the thrust-plane.[2] One of the sets of grooves "is parallel to the dip, the other is inclined at an angle of about 30° in a NE–SW direction."[3]

Although the grooves are not part of the fault-planes proper, but occur on what seem to be irregular fragments of sandstone wedged in front of the fault, their constancy on seemingly different planes at points 500 feet apart can hardly be looked on as due to purely local movements. They are more likely the direct result of the last movements along the major thrust-plane and essentially parallel to them.

If the joints in the vicinity of the Apostle Islands really owe their origin to the action of this pressure directed upward at an angle of about 30° toward the northeast, we should find evidence of it in the position of the joint planes themselves. According to the table on page 96 of Thwaites's paper the joints have the tendency to be vertical. From the text we learn, however, in addition that "many of the E–W joints are inclined, usually at a steep angle to the north."[4]

[1] F. T. Thwaites, *op. cit.*, pp. 66, 76, 80, 81. [2] *Ibid.*, p. 83.

[3] *Ibid.*, p. 78. [4] *Ibid.*, p. 94.

When we plot the attitude of these joints, using the stereographic projection as explained on page 10 of this paper, we find that the greatest (compressive) principal stress should have been directed upward from the southwest at an angle of 15° if we assume the E–W joints to dip 70° north, and of 30°, if they dip 50° north.

This correspondence is quite striking and leaves little doubt as to the correctness of this interpretation.

The northwest-southeast tension, indicated by the position of the obtuse angle of the joints in the Apostle Islands, is parallel to the gentle dip of the rocks of the Bayfield Group. Both dip and tension probably resulted from settling along the axis of the Lake Superior syncline simultaneous with the last movements along the thrust-plane.

d) The last two examples serve well to show how important it is that each observation of jointing be studied in its geographical and structural relations to all others. To assemble the joints observed over a large area in a single diagram means to veil their true relationships. A diagram, published by Hobbs in 1905,[1] shows the strike of 1,004 joints measured by Mr. C. G. Brown in the vicinity of Cayuga and Seneca lakes, New York. It clearly indicates the existence of two nearly orthogonal double systems of conjugate joints. A comparison with Miss Sheldon's diagram[2] shows that the earlier diagram represents a composite picture of the joint systems of two different localities, since the vicinity of Cayuga Lake exhibits only one of the two double systems, as described above.

A fine example of carefully recorded data giving definite measurements of strike and dip, and accurate geographical location of every joint measured, may be seen, for instance, in R. S. Tarr's field observations embodied in Shaler's "Geology of Cape Ann."[3]

3. *Greatest compression horizontal, least compression vertical.*—The position of the principal stresses and of the resulting planes

[1] W. H. Hobbs, "Examples of Joint-controlled Drainage from Wisconsin and New York," *Jour. Geol.*, Vol. XIII (1905), p. 370.

[2] *Loc. cit.*, p. 66.

[3] N. S. Shaler, "The Geology of Cape Ann, Massachusetts," *Ninth Ann. Rep., U.S.G.S.* (1889), pp. 597–602 and Pls. 72–74.

of shearing for this grouping of stresses is represented diagrammatically in Figure 8; Figure 9 illustrates the occurrence of this type in nature on a small scale.[1] It shows "symmetrical faults" in a hard encrinal layer a foot or two in thickness in the Hamilton shales, exposed along the shores of Cayuga Lake. "The exposures of this layer along the lake show faults every few feet." "The strike of the majority is from 20–25° north of west." "Their inclination is sometimes south and sometimes north and the angles are nearly

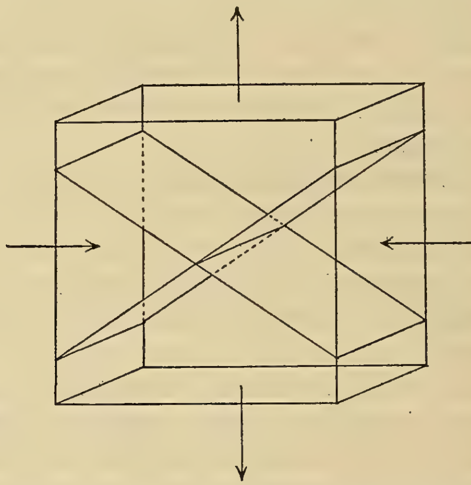
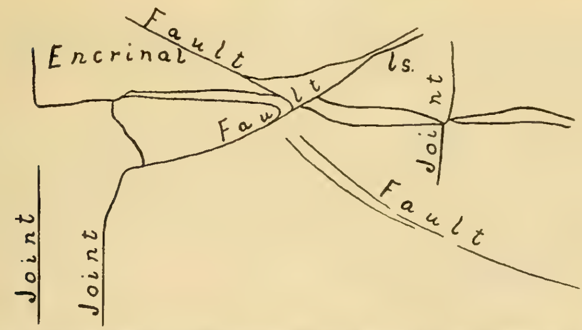


FIG. 8.—Diagram illustrating the position of the planes of shearing in a brittle body subjected to compression in a horizontal direction with the direction of easiest relief (least principal stress) vertical.

the same in the two cases, making the faults symmetrical about a nearly horizontal plane." "The hade varies from 45° to 75°, but most are near the average, which is 62°." The fault surfaces are slickensided and covered with strong, even striations. "The vertical displacement along these faults is from a fraction of an inch to three inches." The faults "usually continue for a few feet in the adjacent shale, but instead of continuing with the same hade, they flatten out and become nearly horizontal in the shales where no hard layer is present."[2]

[1] Pearl Sheldon, "Some Observations and Experiments on Joint Planes," *Jour. Geol.*, Vol. XX (1912), Fig. 3, p. 61.

[2] *Ibid.*, pp. 60–62.



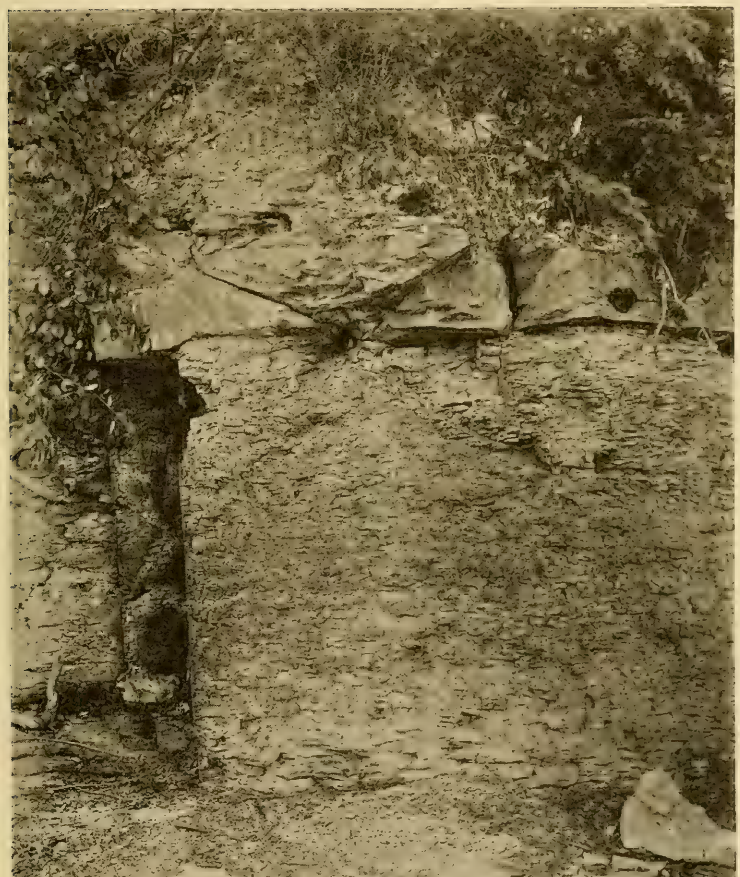


FIG. 9.—Planes of shearing due to stress relations similar to those illustrated in Fig. 9. Bed of hard encrinal limestone in Hamilton shales, exposed along shore of Cayuga Lake. (P. Sheldon, 1912.)

Horizontal faults "occur by the score in the shale beds," usually offsetting the vertical joints for distances often measuring several inches.

These "faults" are unquestionably shearing planes forming an acute angle of approximately 60° facing the direction of the horizontal compressive stress which is clearly manifested in the differential movement between adjoining layers of shale referred to above as "horizontal faults."

Identical results have been obtained in the laboratory, whenever sufficiently brittle materials were subjected to horizontal compression in the course of experiments on overthrusting,[1] and before our eye loom up the sections of the mountain ranges which these experiments were to help explain, with thrust faults in astonishing numbers and on gigantic scales.

Here the subject of our discussion assumes different proportions. We realize that the grouping of stresses resulting in the formation of any of the fracture systems discussed before remains the same whether the fracturing finally results in the formation of vast lines of displacement generally referred to as major faults, which may bound mountain ranges or even continents, or ends with the production of minute cracks which, filled with white calcite, form a delicate network on the dark rock and, found on the surface of flat pebbles on the wet beach, are the delight of children.

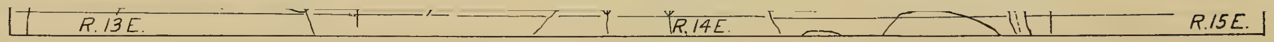
Before we can extend the application of Hartmann's law to the larger scale of the great overthrusts of folded mountains, we must first answer a question which now assumes fundamental importance: Is the angle of shear, in a given substance, sufficiently constant under widely different conditions of pressure and temperature so as to exclude the possibility of grave errors in its use?

We may approach this question best by turning to the ingenious mathematical theory which Mohr has given to account for the results of Hartmann's and others' experiments.

[1] See, for instance, H. M. Cadell, "Experimental Researches in Mountain Building," *Trans. Roy. Soc. Edinburgh*, Vol. XXXV (1890), pp. 337–57; and R. T. Chamberlin and W. Z. Miller, "Low-Angle Faulting," *Jour. Geol.*, Vol. XXVI (1918), pp. 1–44, especially Fig. 9.

Note, however, that the position of the strain ellipsoids in the rigid layers in Fig. 10 does not correspond to the writer's interpretation.

[*To be continued*]


R.13E.
R.14E.
R.15E.

GEOLOGIC RECONNAISSANCE OF THE SOUTHERN PART OF THE TAOS RANGE, NEW MEXICO

JOHN W. GRUNER
University of Minnesota

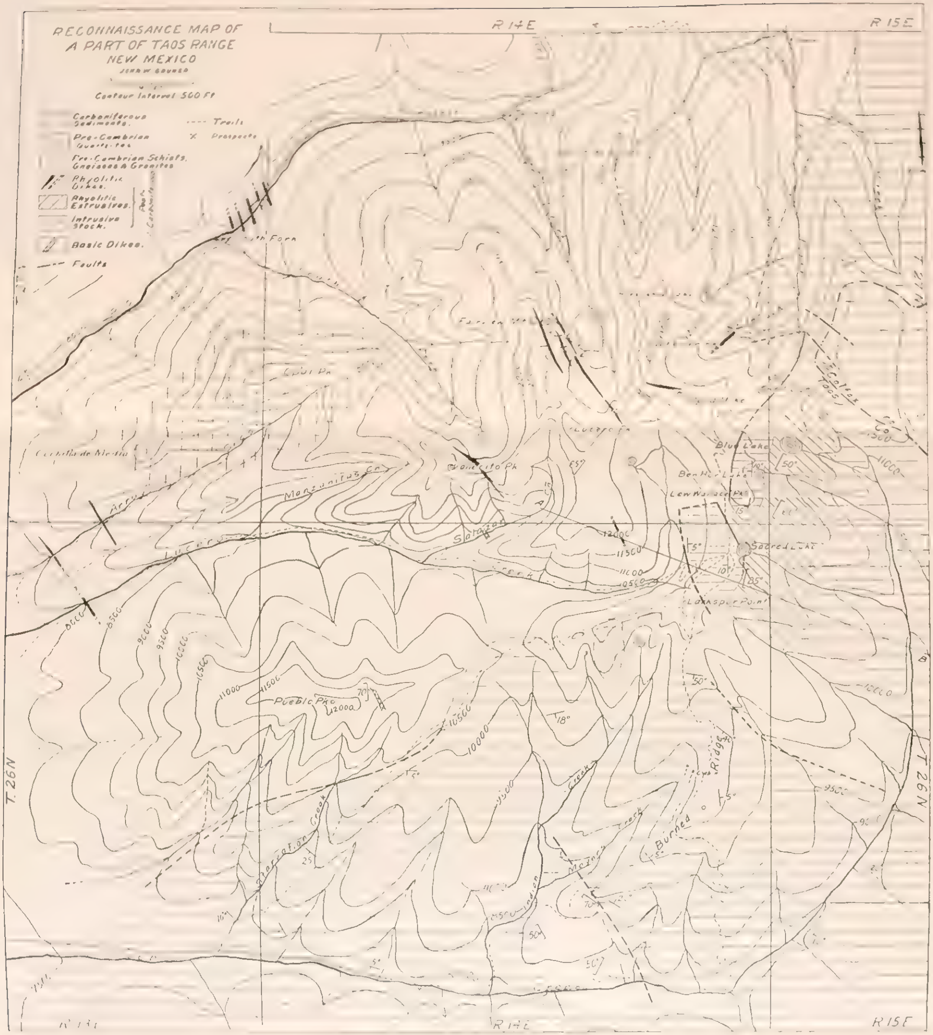
INTRODUCTION

The Taos Range is a part of the Sangre de Cristo Range. Not more than about two-fifths of the Sangre de Cristo Range extends into New Mexico. The larger portion, the Culebra Range and the Sierra Blanca, lies in southern Colorado. Where the Culebra Range crosses the boundary line into New Mexico it splits into two great uplifts, the Taos Range and the Cimarron Range, which find their continuation in the Mora Range and Las Vegas Range respectively. The Taos Range proper is about 30 to 35 miles long and has an average width of 15 miles. Its northern limit is Costilla Creek, its southern Ferdinand Creek. The region described in this report is situated in north central New Mexico near the Colorado line. (See Fig. 1.)

The southern part of the Taos Range, as seen from the Rio Grande Valley to the west of it, offers an imposing view. From an altitude of about 7,000 feet, the elevation of the valley above sea-level, a number of peaks rise to snowy heights within a distance of a few miles. The mountain front is deeply incised by Pueblo Creek, Lucero Creek, and Rio Hondo, which flow westward to, the Rio Grande. (See topographic map, Plate XIII.)[1] The Red River (called "Colorado Creek" by Stevenson[2]), of which only a few miles are in the area mapped, has a northerly direction before it turns westward and breaks through the main chain of the mountains below Red River City.

[1] The attached topographic map was made by the writer who used as basis a map compiled by the United States Land Office and the United States Forest Service. The peak which is called Taos Peak by Stevenson is generally referred to as Wheeler Peak now.

[2] John J. Stevenson, "Report upon Geological Examinations in Southern Colorado and Northern New Mexico, 1878–1879," *Report U.S. Geog. Sur. West of the 100th Meridian*, Vol. 3, Supplement, 1881.


RECONNAISSANCE MAP OF
A PART OF TAOS RANGE
NEW MEXICO
Contour Interval 500 Ft
Carboniferous Sediments.
Trails
Pre-Cambrian Quartzites
Prospects
Pre-Cambrian Schists, Gneisses & Granites
Rhyolitic Dikes.
Rhyolitic Extrusives.
Intrusive Stock.
Basic Dikes.
Faults
R 14 E
R 15 E
T. 26 N
Blue Lake
Sacred Lake
Larkspur Point
Pueblo Pk.
12000
Monzanitas Cr.
Salazar
Burned Ridge
Indian Creek
Colfax Co.
Taos Co.
R 14 E
R 15 E

On the east of the Taos Range the broad Moreno Valley separates the Taos Range from the Cimarron Range, which is nearly as high. On this eastern slope of the range watercourses are rather scarce.

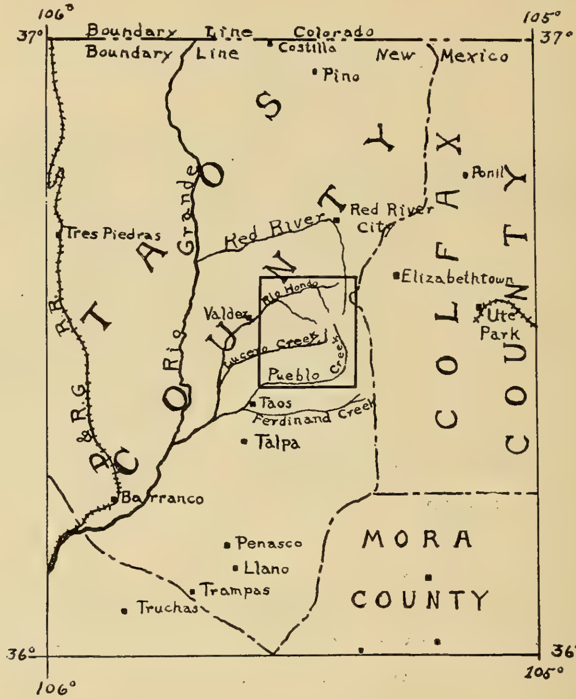


FIG. 1.—North central New Mexico showing location of area mapped. Copied from Plate I of *Professional Paper No. 68.*

DESCRIPTIVE GEOLOGY

The Taos Range is built up of three great rock systems. The pre-Cambrian gneisses, schists, and granites constitute the basement and greater part of the core of the uplift. Upper Carboniferous strata of great thickness are turned up on the east and south sides of the range. These older systems are intruded by stocks and dikes of granite and rhyolite porphyry respectively.

Along the western slope of the mountains large alluvial fans spread over the plains toward the Rio Grande for a number of miles,

where they are finally encroached upon by the basalt flows of the Rio Grande Valley.

In Stevenson's report[1] the mountains north and west of Pueblo Creek are assigned to the "Taos axis," those south and east of that creek to the "Mora axis." It was believed that the Taos axis does not continue beyond Pueblo Creek, but that a new one, the Mora axis, begins at the head of the Red River and runs southward, parallel to the Taos axis on the west, until the latter vanishes. No such structural division could be noticed by the writer between the Taos Range and Mora uplift south of it. The misconception was probably due to the belief that the Pennsylvanian strata exist also on the west side of the range.[2] The sedimentary outliers on the main range, to be described later, when viewed from the distance, easily give such an impression. No new axis begins in this district, but the Taos axis pitches steeply toward the south and the pre-Cambrian rocks disappear at the junction of Pueblo Creek and Indian Creek beneath the Pennsylvanian strata, which form here an uninterrupted anticline across the range.

In the region mapped this anticlinal structure is absent. No Pennsylvanian sediments were found on the western slope north of Pueblo Creek. The mountains present a bold fault scarp facing west. Whether sedimentary rocks of Pennsylvanian age underlie the thick débris fans and basalt flows or not is unknown at the present time. But farther north, in Colorado, Siebenthal mentions their occurrence on the west side of Culebra Peak and the anticlinal structure of the Sangre de Cristo Range at that latitude.[3]

PRE-CAMBRIAN CRYSTALLINE ROCKS

Ancient gneisses and schists.—The most ancient rocks are amphibolite and chlorite schists and gneisses that grade into greenstone in places. They cover the larger portion of the northwestern half of the area mapped, form an almost continuous outcrop along the western scarp of the range, and cap all of the high peaks with the exception of Old Mike. Lack of space will not permit to

[1] *Op. cit.*, pp. 41–42. [2] *Op. cit.*, p. 42.

[3] C. E. Siebenthal, "Geology and Water Resources of the San Luis Valley, Colo.," *U.S. Geol. Survey Water Supply Paper 240* (1907), p. 34.

describe these occurrences in detail, but as a rule sheeting in these rocks has a steep westerly to northwesterly dip. Nowhere in the ancient rocks were any close folds or signs of distortion and twisting seen, as might be expected in schists, and as were actually observed in the metamorphosed sedimentary rocks described below.

Granitic gneisses occupy a rather obscure position with respect to the more basic varieties, and may, in some cases, be of the same age as the batholithic granite intruding the older schists. In one instance, on Old Mike, this relationship was proved. Here the gneiss could be traced to its parent rock, the granite beneath.

The following outcrop deserves special attention in the opinion of the writer. The plateau south of Lucero Peak, between the Salazar and Lucero Canyon, is covered with a dark-green, fine-grained hornblendite and greenstone which resemble a flow. A "sheet" at least 200 to 300 feet thick, of dark, indistinctly schistose rock, overlies the granitic batholith. Ramifying apophyses from the granite beneath can be seen in the greenstone. Just north of Lew Wallace Peak lies a relatively small mass of greenish-gray, very fine-grained altered diabase. No cleavage or regular sheeting is visible in it. Whether this rock bears any genetic relation to the sheet on the opposite side of Lucero Canyon, just described, or not could not be determined.

Metamorphosed sedimentary rocks.—The metamorphosed pre-Cambrian sediments occupy belts of greatly varying width between the Pennsylvanian series on the southeast and the granite batholith on the northwest. The assumption that the batholithic granites are younger than the metamorphosed sediments is based upon the attitude of these formations, which flank and abut against the gneisses and granites. (See Fig. 2.) The formations are chiefly composed of quartzites and quartz and chlorite schists, and are undoubtedly of sedimentary origin.

The area of quartzite as outlined on the map claims accuracy only along the western margin. The eastern limit could only be estimated; therefore the outcrop may be somewhat narrower. The dip of the quartzite is steeply eastward, varying from 45° to 90°. Jointing at right angles to the beds is the rule. Figure 3 shows a nearly perpendicular exposure of quartzite, 300 feet high,

northeast of Ben Hur Lake. No trace of the bedding of the original sandstone was detected, perhaps due to the possible identity of the original bedding and the sheeting. The attitude and character of the quartzite strongly suggest this possibility to the writer. The color of the formation as a whole is yellow, but the southern end of it becomes reddish and purplish gray.

Southeast of Sacred Lake the very steeply dipping quartzite overlies a very much folded and twisted, thinly laminated chlorite schist. The foliation of the latter, as a whole, is parallel to that of quartzite. What appears to be a continuation of the quartzite

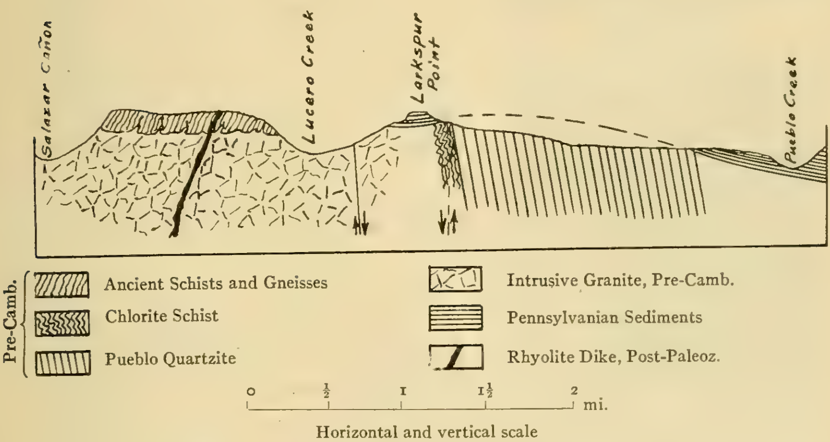


FIG. 2.—Cross-section from Salazar Canyon to Pueblo Creek, along line *A-B* on map.

and schist is seen half a mile southwest of this locality, just below Larkspur Point. Here steeply tilted chlorite epidote schist forms a cliff of conspicuous gray color. Strike and dip of the sheeting are very similar to that of the quartzite. Southwest of Pueblo Peak, adjacent to and north of the Pennsylvanian sediments, steeply inclined quartz-schist forms sharp craggy outcrops and cliffs. The formation flanks Pueblo Peak parallel to the fault line for an unknown distance toward the west.

Intrusive granites.—The distribution and composition of the granites suggest a close genetic connection between the individual areas. It is highly probable that all belong to one great batholith

which arched up the overlying formations and metamorphosed the sediments.

One of the largest exposures of this batholith is along the Rio Hondo, where a light-gray, very coarse biotite granite outcrops. It weathers easily and forms curiously shaped pinnacles in some places. Also along Lucero Creek a pinkish, more or less gneissoid, granite is found. The latter is also the predominating rock in the Salazar Canyon, and from here a broad belt of it passes beneath Lucero Peak to Old Mike.

FIG. 3.—Pueblo quartzite on Ben Hur Lake. Looking northeast. Unconformity on upper left. Pennsylvanian beds nearly at right angles to sheeting of quartzite.

The rocks from Old Mike and Red Dome show every gradation from a typical red granitic gneiss to a medium-grained biotite granite. Medium-grained biotite granite varying in color from pink to greenish gray also covers a large part of Red River Canyon, especially on the west side. A detailed examination was impossible in this part of the district.

Half a mile west of Larkspur Point pink medium to coarse-grained granite outcrops on the steep slope above Indian Creek. South of Larkspur Point the continuation of this outcrop is found in contact with remnants of ancient schist that caps a part of Larkspur Point. Farther toward the southeast the gneissoid granite is exposed along the northwestern tributary of Pueblo Creek for a distance of two and a half to three miles.

Basic dikes.—A number of basic dikes are intrusive into the granite of the batholith. Their age is probably pre-Cambrian. The most prominent one occurs just east of the highest point of Pueblo Peak and has a width of 100 to 150 feet. Its trend corresponds to that of the others, which have a northwest to southeast direction. In composition and texture it approaches a gabbro.

Two pre-Cambrian inliers that cannot be classified outcrop on Pueblo Creek. Quartz and mica schists and some amphibolite are the only rocks in these inliers seen by the writer.

CARBONIFEROUS SEDIMENTARY ROCKS

In the district mapped all sedimentary rocks belong to the Pennsylvanian series. Stevenson[1] described them as Carboniferous, attempting no further divisions then. Later writers, especially W. T. Lee,[2] who examined parts of this series farther east and north, recognized them as belonging to the Pennsylvanian series only. A number of fossils, collected by the present writer near the base of the sedimentary series, belong to the Pennsylvanian fauna. Six species were identified: *Lopophyllum profundum*, *Siminula subtilita*, *Spirifer cameratus*, *Spirifer rockymontanus*, *Productus cora*, *Productus semireticulatus*.

No generalizations concerning the thicknesses and divisions of the series can be given in this paper with the exception of the statement that by far the largest portion of the beds is composed of clastic material. The lowest member is usually a basal conglomerate grading into a sandstone, but in some localities limestone overlies directly the pre-Cambrian, and the sequence is reversed. It is very common to see a limestone in sharp contact with a coarse clastic in some places. On the other hand, formations hundreds of feet thick are found in which the transitions from one member into another are very gradual. Lithologically very similar beds of clastic material occur at many different horizons of the series and some of them are of such thickness that even considerable displacements by faults may be easily overlooked. The fact that all the faults seen by the writer in the sediments are normal and that evidence of folding due to lateral compression is absent seems to indicate that the Taos Range, if not the whole Sangre de Cristo Range, was formed solely by intrusive activity, probably in early Tertiary time.

[1] *Op. cit.*

[2] W. T. Lee, "Geology and Paleontology of Raton Mesa and Other Regions in Colorado and New Mexico," *Prof. Paper 101* (1918), pp. 41–42.

Distribution of the sediments.—The sedimentary rocks cover portions of the Pueblo Creek and Red River drainage basins, and extend far beyond the southern and eastern margins of the area mapped. While the thickness of the formations may be estimated at several thousand feet, at least 2,500 feet in the southeast corner of the district, erosion has reduced the thickness of the sediments toward the northwest to less than 300 feet above Sacred Lake.

The contact of the sediments with the pre-Cambrian rocks follows approximately a line from the southwest corner of the quadrangle to a point on Starvation Creek, about 1 mile south of Pueblo Peak. A normal fault of unknown displacement, probably relatively small, has sharply upturned the sandstones and limestones against quartz-chlorite schists west of Starvation Creek. Here at the bottom of the creek 100± feet of dense gray non-fossiliferous limestone are seen the base of which is not exposed. On it rests a dense, brownish-gray, arkosic sandstone that is brownish red when weathered. This rock caps most of the ridges and is of great thickness.

Farther east, on the high divide between Pueblo Creek and Lucero Creek, the foregoing limestone is overlain by a greenish-gray calcareous and arkosic grit. This grit is of wide extent and great thickness, not only in this district, but beyond its limits. At certain horizons this rock is replete with fossil fragments, especially crinoid stems. It becomes gradually coarser toward the top of the formation and changes to a conglomerate which contains subangular pebbles of quartz, gneiss, granite, and schist. They do not exceed a diameter of 1 inch, but attain greater dimensions on Burned Ridge.

About 1½ miles south of Larkspur Point, where the strata rest on pink granite, the beds dip steeply soutwestward. The basal conglomerate clearly derived from the pre-Cambrian rocks beneath grades into sandstones, grits, and conglomerates. They are of great thickness and constitute no definite, sharply separated members. The attitude of the beds in connection with the dip of the same formation in the opposite direction on the southwest slope of Burned Ridge, near a point where a fault crosses Meyer's Creek, indicates a synclinal structure whose axis runs at right angles to Burned Ridge and pitches southeast.

At the head of Pueblo Creek the Pennsylvanian rests on pre-Cambrian quartzite. A north-south fault crosses the divide between Red River and Pueblo Creek, bringing the sandstones and grits into juxtaposition to the granite on the west. A little farther north two minor step faults cross the ridge from northwest to southeast. North of this exposure the sedimentary rocks are confined almost entirely to the area east of Red River. The river has cut a deep canyon into the sedimentaries, exposing on the east slope a thickness of nearly 1,000 feet of the Pennsylvanian. About 200 feet above the creek bottom the following approximate section is exposed:

	Feet
Red sandstone, very fine grained	100–150
Arkosic, light-colored sandstone, at least	200
Gray, fossiliferous limestone	50±
Dark-gray shale, carbonaceous in places	50±
Light-gray quartz conglomerate	40±
Concealed base	.....

A number of outliers of the Pennsylvanian are situated on the east slope of the main range and extend from Bull of the Woods to the head of Indian Creek. The most interesting outlier, a block faulted down on at least three of its four sides, lies east of Larkspur Point. (See Fig. 2.) A partial section of it measured just south of Sacred Lake is given below:

	Feet
15. Light-gray, very hard and massive arkosic sandstone	15
14. Brownish-gray, shaly limestone	30
13. Lime cemented conglomerate (description below)	20
12. Puddingstone conglomerate	10
11. Dark-red, very dense shale	20
10. Light-gray arkosic sandstone	12
9. Puddingstone conglomerate	25
8. Gray, massive, argillaceous limestone	45
7. Light-brown, medium-grained calcareous grit	20
6. Grayish-green shale, non-laminated	6
5. Puddingstone conglomerate (very coarse)	25
4. Brownish-gray, gritty limestone, fossiliferous	21
3. Red shale, somewhat arenaceous	9
2. Puddingstone conglomerate (extremely coarse)	32
1. Dark-red, very dense, massive shale	15+
	305

Concealed base about 50+ feet above schist

Of special interest in the outlier are the five members listed as puddingstone conglomerates on account of their unusual texture and composition. Their color as a whole is dark red. Joints and bedding planes are few and far apart in the three lower members. The lowest one (No. 2) of the formation consists of very angular "pebbles" and platy fragments of green chlorite and gray quartz-schist and gray slate, varying in size from mere sand grains to great bowlders 3 to 4 feet in diameter. They are imbedded in a red argillaceous and arenaceous cement, which makes up 80 to 85 per cent of the volume of the conglomerate. The highest member of the conglomerates (No. 13) which contains pebbles not exceeding 1 inch in diameter has only calcite as cement, which contains abundant fossil fragments.

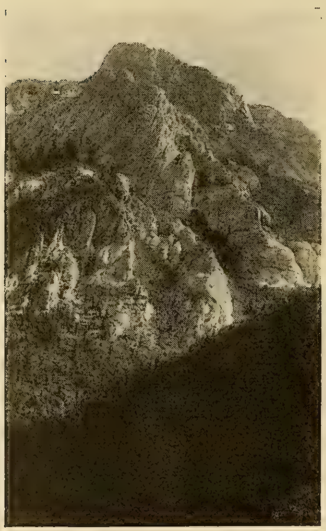


FIG. 4.—Opal Peak. Looking northeast. Center of porphyry stock with nearly vertical sheeting.

POST-PALEOZOIC IGNEOUS ROCKS

Though outcropping in areas 5 to 7 miles apart, the Red River rhyolite flow, the intrusive Opal Peak porphyry, and the numerous rhyolitic dikes are chemically and mineralogically much alike and probably of the same age. They are certainly post-Carboniferous, for one of the dikes cuts the Pennsylvanian beds on the divide east of Red River.

Only a part of the thick rhyolite porphyry flow on Red River lies in the area mapped. The rock is light gray in color. The white porphyry of the extremely rugged Opal Peak and Cuchilla de Media lying between the darker gneisses and granites offers a conspicuous color contrast. The porphyry in spite of its prominent sheeting (Fig. 4) is very soft, and no dark minerals were seen in it.

The scattered white rhyolite porphyry dikes, intrusive into the pre-Cambrian rocks, as a rule have a northwesterly trend and steep or vertical dip.

GEOLOGICAL HISTORY

While the pre-Cambrian history of the Taos Range must necessarily remain rather obscure until further investigation and correlation with other regions, some of the events may be enumerated with more or less accuracy. Nothing is known about the origin of the ancient gneisses and schists. During the long erosion interval that exposed them and probably reduced the ancient mountains to base level, thick clastic deposits accumulated along the eastern and southern margins of the area now occupied by the granite batholith.

Upon this time of great erosion a period of intense orogenic movement followed, probably accompanied or closely succeeded by the intrusion of enormous volumes of granitic magma into the overlying schists, gneisses, and sediments. Later a number of basic dikes pushed their way into this batholith. No record of the geologic events that followed is preserved until Pennsylvanian time.

At the beginning of this period the present site of the range most likely formed the eastern shore of a considerable land mass west and northwest of it. Siebenthal, in his study of the San Luis Valley, has come to the same conclusion.[1] The very coarse and angular basal conglomerates of the Pennsylvanian leave no doubt as to the near-shore conditions that existed during their formation. The deposition of the puddingstone conglomerates and breccia and such bowlder beds (some bowlders with a diameter of 25 to 50 feet) as S. F. Emmons mentions farther north, on the east side of the Sangre de Cristo Range,[2] can have been brought about only by talus and wash from a precipitous coast directly into deep or quiet water. The fact that the pebbles of all conglomerates consist of pre-Cambrian schists, gneisses, quartzites, and granites suggests a land surface composed chiefly of these rocks. The enormous thickness of the strata leads also to the conclusion that a gradual sinking of the coast and progressive submergence from the east to the west took place during this period.

[1] C. E. Siebenthal, "Geology and Water Resources of the San Luis Valley, Colo.," *U.S. Geol. Survey Water Supply Paper 240* (1907), pp. 50–51.

[2] S. F. Emmons, "Orographic Movements in the Rocky Mountains," *Geol. Soc. Amer. Bull.*, Vol. I, pp. 245–86.

A more difficult problem arises from the question when deposition of sediments ceased. Stevenson speaks of the Jura Trias "Red Beds" that occur farther east and south as resting conformably upon the Carboniferous.[1] Lee, on the other hand, would rather assign them, at least partly, to the Pennsylvanian system.[2] He also favors the assumption that during Cretaceous time the sea covered practically all of the territory now occupied by the southern Rocky Mountains.[3] Until further evidence is found to prove that this view is correct, the present writer is inclined to believe that the site of the Taos Range proper during the Cretaceous was not, or only for a short epoch, an area of deposition for the reason that no Cretaceous sediments have been discovered on the west side of the Culebra and Mora ranges as far as can be learned from the available literature.

Probably during early Tertiary, deep-seated intrusive activity resulted in the uplift of the Sangre de Cristo Range. Since that time erosion has been at work continually. Glaciation in recent time has been an especially powerful agent in the process of destruction of the mountains.

ECONOMIC GEOLOGY

It is not likely that this district will ever attain great importance on account of its mineral resources. Three deserted camps on the Rio Hondo tell of an attempt to extract gold at South Fork and Almozzet, and copper at Twining. Lindgren has described these occurrences.[4]

A number of short prospect tunnels are situated in and close to some of the rhyolite dikes near Fairview Mountain and Lucero Peak where pyritization has altered the schist. Another claim is at the head of Elm Creek, near the base of the Pennsylvanian, where a narrow vein of barite and galena outcrops in the sediments.

[1] *Op. cit.*, p. 85.

[2] *Op. cit.*, p. 39.

[3] W. T. Lee, "Relation of the Cretaceous Formations to the Rocky Mountains in Colorado and New Mexico," *U.S. Geol. Survey Prof. Paper 96* (1916), p. 40.

[4] W. Lindgren and L. C. Graton, "The Ore Deposits of New Mexico," *U.S. Geol. Survey Prof. Paper 68* (1910), p. 83.

SUMMARIES OF PRE-CAMBRIAN LITERATURE OF NORTH AMERICA

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III. QUEBEC

THE EASTERN PART OF CANADA, NEWFOUNDLAND, AND GREENLAND

Recent studies of the pre-Cambrian in Nova Scotia and Newfoundland have been of a reconnaissance nature and do not modify earlier stratigraphic studies in any important way. In northern Quebec, Cooke, Wilson, and Tanton have extended reconnaissance mapping to new areas. Moore has studied the Belcher Islands of James Bay and finds a series of slates, graywackes, quartzites, limestones, and sandstones similar to the Nastapoka and Richmond groups described by Leith and Low. In northern Quebec, the succession from the base upward includes mainly (1) basic lavas, ferruginous dolomites, iron formations, rhyolites, other volcanics of the Keewatin type, etc.; (2) crystalline limestones, etc., of the Grenville type; (3) intrusives of granite and granite gneiss. In western Quebec, Timiskaming County, rocks of the preceding type are unconformably overlain by conglomerates and other poorly sorted clastics. The youngest rocks are basic intrusives. The sections made do not all agree as to the relative position of the Grenville and Keewatin types.

Buddington[1] finds that the Algonkian rocks of southeastern Newfoundland include 16,000 feet of sediments intruded by granite, syenite, and gabbro, basic and acid dikes and flows. The sediments consist of green and purple cherty slate, volcanic conglomerate, and upper series 6,000 to 7,000 feet thick of red and green sandstones, conglomerates, and shales, containing fresh feldspars, cross-bedding, and intra-formational conglomerates. The upper sediments show evidence of continental origin.

[1] A. F. Buddington, "Reconnaissance of the Algonkian Rocks of Southeast Newfoundland" (Abstract), *Bull. Geol. Soc. Am.*, Vol. XXV, No. 1 (1914), p. 40.

Buddington[1] studies the petrography and origin of the pre-Cambrian rocks of Newfoundland.

Cooke[2] says that the underlying rocks of the region at the head waters of the Broadback River in northwestern Quebec include a complex of basic schists, which is overlain unconformably by sediments including mica quartz schists, quartzites, arkose, and conglomerate. The youngest rocks are intrusive granites.

Cooke[3] states that the pre-Cambrian rocks of the northwestern part of Quebec are probably all pre-Huronian, using the latter term in the sense of the International Committee. The succession is as follows:

Mattagami series—In scattered patches
Unconformity
Nemenjish series—Seems to correspond to Grenville series farther south
Abitibi series—Basic lavas probably the equivalent of the Keewatin

Dresser[4] reports on an area along the south shore of Lake St. John about 120 miles north of the city of Quebec. Here are notable outliers of Paleozoic rocks preserved by faulting. The pre-Cambrian rocks of the area include granites and anorthosite, the latter containing important titaniferous magnetic ores.

Faribault[5] reports that the pre-Cambrian rocks of the Pleasant River Barrens, Lunenberg County, Nova Scotia, comprise the Goldenville quartzite which is overlain by the Halifax slates.

According to Faribault[6] the pre-Cambrian rocks underlying the Port Mouton map area comprise the Goldenville quartzite

[1] A. F. Buddington, "Pre-Cambrian Rocks of Southeast Newfoundland," *Jour. Geol.*, Vol. XXVII (1919), pp. 449–79.

[2] H. C. Cooke, "An Exploration of the Headwaters of the Broadback or Little Nottaway River, Northwestern Quebec," *Canada Geol. Surv. Summ. Rept. 1912* (1914), pp. 337–41, map.

[3] H. C. Cooke, "Some Stratigraphic and Structural Features of the Pre-Cambrian of Northern Quebec," *Jour. Geol.*, Vol. XXVII (1919), pp. 65–78, 180–203, 263–75.

[4] John A. Dresser, "Part of the District of Lake St. John, Quebec," *Canada Geol. Surv. Mem. No. 92* (1916), 88 pp., 5 pls., 2 figs., map.

[5] E. R. Faribault, "Geology of the Gold District of Pleasant River Barrens, Lunenberg County, Nova Scotia," *Canada Geol. Surv. Summ. Rept. 1913* (1914), pp. 259–63, map.

[6] E. R. Faribault, "Geology of the Port Mouton Map Area, Queens County, Nova Scotia," *Canada Geol. Surv. Summ. Rept. 1913* (1914), pp. 251–58.

18,348 feet in thickness and the Halifax slates 11,700 feet thick which overlie it.

Hovey[1] states that Archean gneisses appear on Parker Snow Bay, Greenland. They are overlain by Huronian quartzites, quartz schists, etc.

Malcolm[2] reports that the gold fields of Nova Scotia occupy the eastern half of the province bordering the coast. The oldest rocks are either Cambrian or pre-Cambrian sediments consisting of the Goldenville quartzites 16,000 feet thick conformably overlain by the Halifax slate 14,500 feet thick. Unconformably overlying them are Devonian or Carboniferous sediments. The quartzites and slates are thrown into folds having an east to west trend. Locally they are altered into gneisses and schists by a granite intrusion.

Moore[3] finds over 9,000 feet of pre-Cambrian sediments on Belcher Islands about seventy miles from the south coast of Hudson Bay. These sediments resemble the Nastapoka and Richmond groups described by Leith and Low. The sediments include iron formation, concretionary limestone, and dolomite, various slates, some of which show marked banding, quartzites, graywackes, and sandstones. The iron formation consists of jaspilite, chert, cherty-iron carbonate, green granules probably iron silicate, hematite, magnetite, and shale. Diabase sills and basalt flows of uncertain age are associated with the sediments. Moore concludes from his study of the concretionary structures of the limestones and the granular structures of the iron formations that they were formed in part by algae and other lowly organism. The chief source of the iron solutions, he believes, was lateritic weathering.

[1] E. O. Hovey, "Notes on Geology of the Region of Parker Snow Bay," *Bull. Geol. Soc. Am.*, Vol. XXIX (1918), p. 98.

[2] Wyatt Malcolm, "Gold Fields of Nova Scotia," *Canada Geol. Surv. Mem. No. 20* (1912), 331 pp., 42 pls., 24 figs., 2 maps.

[3] E. S. Moore, "The Iron Formation on Belcher Islands, Hudson Bay with Special Reference to Its Origin and Its Associated Algal Limestones," *Jour. Geol.*, Vol. XXVI (1918), pp. 412–38, 18 figs.

Tanton[1] maps and describes an area northeast of Lake Abitibi. His succession of pre-Cambrian rocks follows.

Post batholithic intrusives
    Olivine diabase
Keweenawan
    Quartz diabase, minette
Batholithic intrusives
    Granite and granite gneiss
Laurentian
    Igneous contact
Harricanaw series
    Arkose, conglomerate, graywacke
    Unconformity
Abitibi group
    Ferruginous dolomites and iron formation rhyolites, basalt, other volcanics, etc.

The Kewagama Lake area described by Morley E. Wilson[2] includes about eighty square miles bordering on the Province of Ontario. Cobalt is about thirty miles south of the southwest corner of the area.

The region is a peneplain whose elevation above sea-level varies from 900 to 1,100 feet. The divide between the James basin and the St. Lawrence system crosses it along a sinuous east and west line. Many of the low hills and streams of the region are parallel with the rock structure, most of which trends north of east. Some of the streams and lakes, however, have a strikingly linear north and south direction. Wilson believes that they follow preglacial depressions.

The bed rocks are all pre-Cambrian. In many places they are covered by stratified and unstratified glacial deposits and by postglacial, finely stratified lake clays and sands. Wilson classifies the pre-Cambrian rocks into two main divisions, but refrains from correlating them with any of the units recognized by the International Committee.

The oldest division consists of highly metamorphosed and folded rocks intruded by batholiths of granite and granite gneiss.

[1] T. L. Tanton, "The Harricanaw Turgeon Basin, Northern Quebec," *Canada Geol. Surv. Mem. No. 109* (1919), 84 pp., 1 map, 9 pls., 2 figs.

[2] Morley E. Wilson, "Kewagama Lake Map Area, Quebec," *Canada Geol. Surv. Mem. No. 39* (1913), pp. 39–122, 24 pls., 9 figs., map in pocket.

The intrusive granites and granite gneisses resemble the Laurentian. They intrude the Abitibi group. The latter include a volcanic complex, consisting of amphibolites and schists, chloritic rocks, slate, and ferruginous dolomite; and the Pontiac series of fine-grained mica schists and gneiss, hornblende schist, amphibolite, arkose, graywacke, and conglomerate.

This old complex is beveled by a pre-Cambrian peneplain above which lies the Cobalt series. The contact is sharp in places; in others it is gradational. The Cobalt series consists of two tillite-like conglomerates separated by even-bedded graywacke, argillite, quartzite, and arkose. The conglomerates are believed by Wilson to be glacial because of their heterogeneous character, their great extent, the size of some of the constituent bowlders, the distance of some of the bowlders from the parent ledge, the soled and striated nature of some of the bowlders, the improbability that the large bowlders could have been deposited from checked torrential streams, since they rest on a peneplained surface on which streams must have had a low gradient. The stratified deposits separating the conglomerates are believed by him to be of interglacial, lacustrine origin.

The Cobalt series are intruded by a mass of syenite porphyry classed as doubtfully Keweenawan. Considered as doubtfully of the same age are certain diabase dikes which cut the old complex, but are not known to intrude the Cobalt series. They are called the Nipissing diabase because of their lithologic similarity to the Nipissing diabase of the Cobalt district.

Wilson[1] presents a map and report on Timiskaming County, Quebec. An outline of his classification of the pre-Cambrian rocks follows.

Keweenawan—Basic intrusives
Huronian—Cobalt series
        Conglomerate
        Arkose
        Graywacke and Argillite
    Unconformity

[1] Morley E. Wilson, "Timiskaming County, Quebec," *Canada Geol. Surv. Mem. No. 103* (1918), 196 pp., 1 map. 16 pls., 6 figs.

Basal complex
- Pre-Huronian—Batholithic intrusions, granites, etc.
- Abitibi group
  - Pontiac series—Sedimentary schists, iron formation, etc.
  - Igneous intrusives—Chiefly basic
  - Extrusives—Chiefly basic
- Grenville series
  - Crystalline limestone, etc.

As in certain other recent papers by Wilson, he argues for a local nomenclature of the pre-Cambrian and against extensive correlations.

Wilson[1] reports that the succession of rocks underlying a part of Amherst Township of Quebec about 60 miles northeast of Ottawa, is as follows.

Late pre-Cambrian—A single diabase dike
Basal complex—
- Batholithic granite and syenite gneiss
- Buckingham series of intrusives—Gabbro, pyroxene, syenite, anorthosite
- Grenville series—Limestone, garnet, gneiss and quartzite

Wilson[2] reports on a geological reconnaissance of a part of northwestern Quebec. The region includes a southern limestone belt, Grenville series, a northern sedimentary and volcanic belt (Abitibi group), and an intermediate belt of banded gneisses largely igneous intrusives into the Abitibi group. The Abitibi group includes schists, iron formations, and conglomerates which have not been stratigraphically separated.

Wilson[3] concludes that the banded Laurentian gneisses are mostly of igneous origin and owe their banding to differentiation under deformative conditions, the latter causing fractures in the crystallized portions which become filled with magma.

[1] Morley E. Wilson, "Geology and Mineral Deposits of a Part of Amherst Township, Quebec," *Canada Geol. Surv. Mem. No. 113* (1919), 54 pp., 1 map, 17 pls., 3 figs.

[2] Morley E. Wilson, "A Geological Reconnaissance from Lake Kipawa via Grand Lake Victoria to Kawikawinika Island, Bell River, Quebec," *Canada Geol. Surv. Summ. Rept. 1912* (1914), pp. 315–36, fig.

[3] Morley E. Wilson, "The Banded Gneisses of the Laurentian Highlands of Canada," *Am. Jour. Sci.*, 4th Ser., Vol. XXXVI (1914), pp. 109–22.

Wright[1] says that the pre-Carboniferous rocks of the Clyburn Valley, Cape Breton, consist of a bedded series of volcanics invaded by quartz diorite and granite batholiths and by sills and dikes of basic materials.

IV. MANITOBA, SASKATCHEWAN, AND NORTHWEST TERRITORIES

Alcock[2] has made a reconnaissance of the Lower Churchill River region of Manitoba and reports that the pre-Cambrian rocks of the area include the following:

Pre-Cambrian		
	Granite and gneiss	Biotite granite gneiss, hornblende granite gneiss, amphibolite, granodiorite, porphyritic granite
	Churchill quartzite	Dominantly a dark gray, fine-grained quartzite
	Keewatin	Local areas of chloritic and sericitic schists

Bruce[3] has mapped and described the Amisk-Athapapuskow Lake area on the western border of the Canadian Shield on the boundary line between Saskatchewan and Manitoba. His succession follows:

		Kaminis granite Granite gneiss Hybrid granitic rocks
Intrusive contact		
Upper Missi series	Arkose Conglomerate	
Unconformity		
Lower Missi series	Slate Graywacke Quartzite Conglomerate	
Unconformity		
	Cliff Lake granite porphyry	
Intrusive contact		
Kisseynew gneisses		
Amisk series	Sedimentary and igneous gneisses and schists, lavas, tuffs, agglomerates, and derived schists	

[1] W. J. Wright, "Geology of Clyburn Valley, Cape Breton Island (Nova Scotia)," *Canada Geol. Surv. Summ. Rept. 1913* (1914), pp. 270–83, map, diagram.

[2] F. J. Alcock, "Lower Churchill River Region, Manitoba," *Canada Geol. Surv. Summ. Rept. 1915* (1916), pp. 133–36.

[3] E. S. Bruce, "Amisk-Athapapuskow Lake District," *Canada Geol. Surv. Mem. No. 105* (1918), 91 pp., map, 7 pls., 4 figs.

Camsell[1] reports on the results of a reconnaissance of a portion of the northwest territories between longitudes 108°30′ to 114°30′ and latitudes 58°30′ to 61°30′. His classification of the pre-Cambrian rocks of the area follows.

Athabaska sandstone (sandstone and conglomerate)
  Unconformity
Granite and gneiss
  Intrusive contact
Tazin series (mica, chlorite, and quartz schists, slates and limestone)

Camsell and Malcolm[2] present a reconnaissance map and report of the Mackensie River basin between longitude 100° to 135° and latitudes 55° to 68°. Pre-Cambrian rocks occur along the eastern border of the basin. Their classification of the succession follows.

Late pre-Cambrian	Sandstone, limestone, and basic flows and intrusives
Unconformity	
Granite and gneisses	
Intrusive contact	
Early pre-Cambrian	Schists, slates, limestones, and quartzites

McInnes[3] reports on a reconnaissance of 220,000 square miles lying between 91° to 106° longitude and 53° to 59° latitude. The area extends from Lake Winnipeg to Fort Churchill on Hudson Bay eastward to Prince Albert. The area is underlain chiefly by pre-Cambrian rocks excepting on the southwest corner, which is underlain by Cretaceous. Most of the pre-Cambrian rocks resemble the Laurentian of the Lake Superior region. In the eastern portion are found patches of the Keewatin and Grenville type. Sandstones like the Keweenawan of Lake Superior are abundant in the northwest part of the area. The classification of the pre-Cambrian by McInnes follows.

Keweenawan? Athabasca sandstone—White and dull red, coarsely granular, siliceous sandstone and conglomerate in thick, horizontal beds

[1] Charles Camsell, "An Exploration of the Tazin and Taltson Rivers, Northwest Territories," *Canada Geol. Surv. Mem. No. 84* (1916), 124 pp., 18 pls., 1 map.

[2] Charles Camsell and Wyatt Malcolm, "The Mackensie River Basin," *Canada Geol. Surv. Mem. No. 108*, 154 pp., 1 map, 14 pls.

[3] William McInnes, "The Basins of Nelson and Churchill Rivers," *Canada Geol. Surv. Mem. No. 30* (1913), 146 pp., 19 pls., 1 map.

Laurentian	Biotite granite gneiss, hornblende gneiss, amphibolite, granodiorite, etc.
Grenville ?	
(Lac La Ronge series)	Quartz diorites, pyroxenites, amphibolites, gneisses, and schists, and crystalline limestones
Keewatin	Chloritic and hornblende schists, diorites, hornblendites, serpentines, etc.
Igneous	Granites, pegmatites, diorite, dikes, younger than Laurentian

The pre-Cambrian[1] rocks east of the south end of Lake Winnipeg are provisionally classified as:

Post Lower Huronian	Manigolagan granite, Pegmatite and gneiss
Huronian	Wanigow series; conglomerate containing quartz, rhyolite granite, felsite, greenstone, jasper, and chert, maximum diameter of pebbles 1 foot
Keewatin	Arkose, graywacke, chert, jasper, gray gneiss, and schist
	Rice Lake series; greenstone, quartz porphyry, rhyobite, trachyte felsite, green and gray schist

[1] E. S. Moore, "Region East of the South End of Lake Winnipeg (Manitoba)," *Canada Geol. Surv. Summ. Rept. 1912* (1914), pp. 262–70, map.

[*To be continued*]

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Index to Volume XXVIII